VISUALIZING GLAUCOMA: ACCURATELY CHARACTERIZING AND DEPICTING VISUAL LOSS VIA VIRTUAL REALITY

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Abstract

Glaucoma is the leading cause of global irreversible blindness, affecting more than 70 million people worldwide between the ages of 40 - 80. Tests to diagnose and understand the impact of disease are well established, however the actual patient experience of glaucoma-affected vision has been confined to epidemiologic descriptions of function and imprecise visualization of what the patient sees. Many patients diagnosed with early-stage glaucoma are prescribed life-long therapies, yet they experience minimal visual distortions. The eventual, long-term impact of glaucoma on their activities of daily living and quality of life eludes them, reducing chances for treatment compliance. Furthermore, the limited visual depiction of the disease may prevent providers and family members from providing empathetic care and support.

Existing visualizations portraying the first-person experience of glaucoma suffer from methodological shortcomings. Most current representations are static, 2D images that do not correlate with patient-specific visual field (VF) impairment; these images do not capture or address the variability of vision loss and its effects on the patient's ability to decipher visual information. Moreover, most have not been derived from a systematic, patient-centered approach. Thus, there is a need for better methods to visualize disease from the patient perspective, and new ways to communicate that experience.

This research protocol accomplished these goals through a two-phase process: Phase 1 involved characterizing the visual experiences of several patients with unilateral, moderate to severe glaucoma via a series of custom eye assessments and interviews. Patients with unilateral disease then corroborated the visual differences between their glaucoma-affected and normal eyes. Phase 2 depicted the resulting data through virtual reality (VR) eye-tracking technology in order to demonstrate dynamic aspects of the disease. The final VR application includes: (i) a real-time video feed which represents to patients various glaucoma patient visual field loss patterns derived from our pool of characterized patient data, (ii) an immersive environment for visual search tasks with the option to toggle off representations of the disease state, and (iii) a patient education module with animations outlining the physiology of glaucoma, including links between disease pathology and findings in common tests used to identify and assess progression of disease.

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INTRODUCTION

Glaucoma Overview

Glaucoma is the leading cause of global irreversible blindness, affecting more than 70 million people between the ages of 40 to 80 years old and disproportionately affects African and Asian populations. The statistics project a rise in cases to the hundreds of millions over the coming decades. (Tham 2014).

Glaucoma begins with insufficient aqueous humor drainage or outflow, resulting in high intraocular pressure. In a physiologically healthy eye, aqueous humor (AH) is produced by a structure behind the iris called the **ciliary body.** The AH flows anterior to the iris and is drained primarily through the **trabecular meshwork**. The **drainage angle, located** between the iris and the trabecular meshwork, is what regulates AH outflow (Figure 1).

In some eyes, blockage of the drainage angle causes a buildup of AH within the eye, leading to an increase of intraocular pressure. The outward stress (which also occurs at normal intraocular pressures in some eyes) degrades **retinal ganglion cells**, neurons within the retina that make up the nerve fiber layer (Figure 1). Patients with glaucoma often suffer from cupping of the optic disc, a physical indication of lost retinal ganglion cells axons (Figure 2).

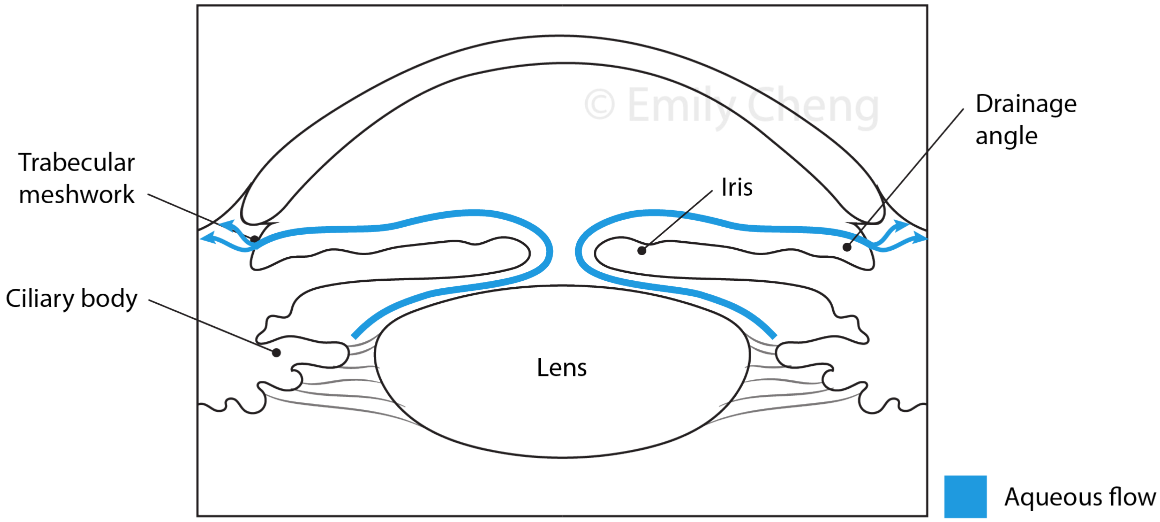


Figure 1. *Diagram of Normal Aqueous Flow with Relevant Eye Anatomy*

Figure 2. *Comparison of a Normal Fundus (Left) and Cupping of the Optic Disc Indicative of Glaucoma (Right).*

There are two main types of glaucoma, open angle glaucoma and closed-angle glaucoma. Each form of the disease has very different treatment approaches and severity of onset. The differences in physiological onset for each type of glaucoma lies in the **trabecular meshwork** and **uveoscleral drainage canals**.

In high tension, open-angle glaucoma, the drainage angle remains open, but the trabecular meshwork becomes dysfunctional for other reasons (in cases occurring at high intraocular pressure), or remains functional (in cases of cases occurring at lower, normal intraocular pressures (Figure 3). In closed-angled glaucoma, or acute angle closure glaucoma, the iris moves anteriorly against the trabecular meshwork, impairing the **drainage canal**. In acute angle closure cases, this causes a sudden severe rise in intraocular pressure which threatens the optic nerve and requires urgent treatment (Figure 3). More commonly, angle closure causes a chronic elevation of intraocular pressure which damages vision over months to years. Regardless of the intraocular pressure, the hallmark of glaucoma is a damaged optic nerve.

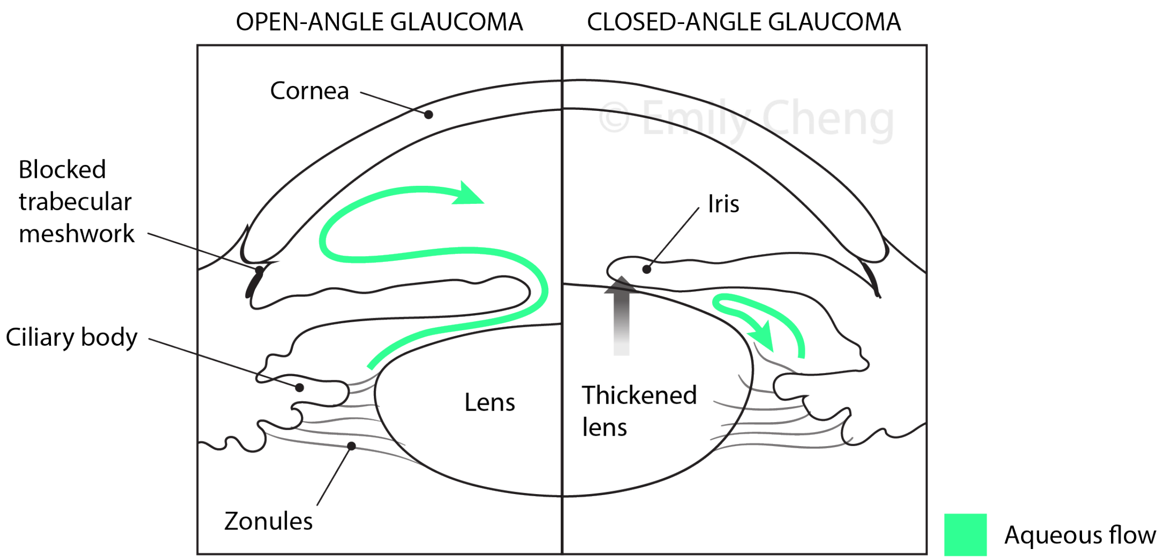


Figure 3. *Open vs. Closed Angle Glaucoma.*

Testing

There are several types of visual exams performed in order to provide quantifiable data regarding the presence/severity of glaucoma. However, the results of these exams fail to fully communicate the visual experience of a person suffering from glaucoma. However, it is still worth discussing the merits and measurable data these vision tests identify.

Humphrey's Visual Field Test (HVF)

The Humphrey Visual Field Test maps out the periphery of a person's visual field as they focus on a central fixation target. A normal visual field extends about 100 degrees temporally, 60 degrees nasally, 60 degrees superiorly, and 70 degrees inferiorly. The most common testing algorithms used to measure patient visual field are the Central 24-2 or 10-2, indicating the degrees from fixation evaluated.

During testing, the patient places their head on a chinrest and fixates their gaze on a center point within a large bowl. Brief light stimuli (~200ms) then appear within different locations at varying sizes and luminous intensity. The patient is tasked with pressing a handheld button whenever they see the stimuli.

Results of the light intensity, or threshold values, that the patient can see is reported in decibels (dB). High values are indicative of greater sensitivity to light at that location. The map will show lighter grayscale regions for higher sensitivity. HVFs also come with a numerical total deviation map (comparing the patient's visual sensitivity to the average individual within their age range), as well as a numerical pattern deviation map that displays differences within a patient's visual field (Carroll 2013).

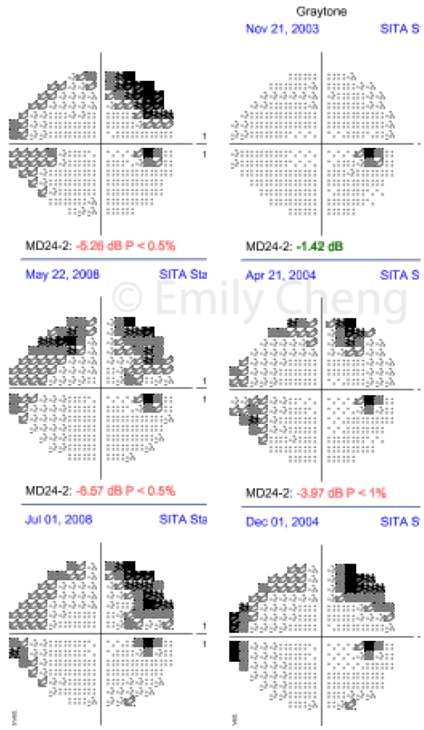


Figure 4. *Sample HVF Test Results. Text not intended to be read.*

Optical Coherence Tomography (OCT)

OCT is an imaging technique that captures cross-sectional retinal anatomy. These images allow for the thickness of the retina and retinal layers to be evaluated (i.e. the retinal ganglion cells or their axonal projections) in real-time. OCT is thus particularly helpful in guiding early diagnosis of ocular diseases like glaucoma.

OCT can be effective at distinguishing normal eyes or physiologic cupping from early glaucoma. In addition, there are two indicators that are particularly reliable in identifying glaucoma – Retinal Nerve Fiber Layer (RNFL) thickness and macular ganglion cell complex thickness. OCT visualizes the thickness of RNFL in a cubic area around the optic disc and is displayed through varying color codes from blue to red, with blue indicating thinner portions. The representation of a pervasive blue pattern around the optic disk can indicate a reduction of retinal ganglion nerve fiber thickness and can point to an early glaucoma diagnosis.

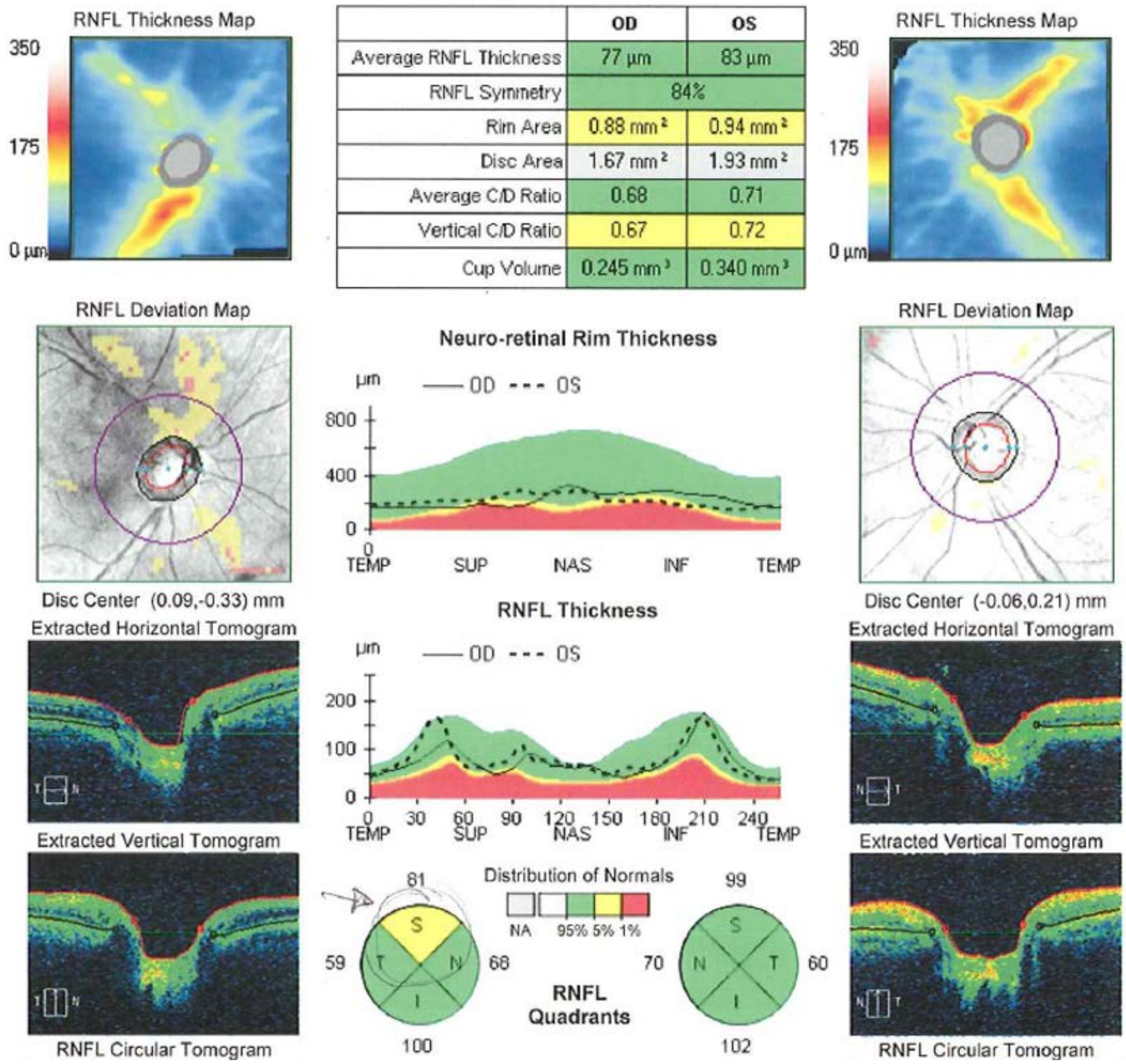


Figure 5. Sample OCT Exam Result and Measurements. Text not intended to be read.

Treatment Plans for Glaucoma

Patients who are diagnosed with early onset glaucoma have several treatment options – all of which are achieved by lowering intraocular pressure. Options typically include prescription eye-drop therapy, office-based laser treatments, or surgery. The most common early-onset treatment is prescription eye-drop therapy, which is a lifelong preventative measure that needs to be adhered to and unfortunately is oftentimes perceived by patients as a daily inconvenience. On the other hand, patients who experience acute close-angled glaucoma suffer episodic medical emergencies and are therefore treated through urgent laser or surgical care. Patients with chronic forms of angle closure glaucoma, which are more common than the acute version, are treated with prescription eye-drops or surgery, most commonly after a laser treatment to prevent pupillary block and open up the angle.

Current Problems with Treatment

For slow progressing, early-onset glaucoma, initial visual deficiencies usually go unnoticed by patients and the inability to see their vision being threatened can often make it difficult for patients to develop the motivation to adhere to lifelong eyedrop therapy. Oftentimes they may feel their vision has not deteriorated and thus their diagnosis remains an abstract concept.

Ophthalmologists responsible for prescribing such long-term therapies may also not fully understand what the patient's visual experience is like. They instead rely on objective testing as well as self-reported assessment of visual loss to inform their decision-making, both of which can be inconsistent and only unveils part of picture. While tests are helpful for the physician to understand a patient's disease, the test results can also be difficult for the average patient to understand and visually interpret. As a result, clinicians may have a difficult time communicating to patients the criticality of ongoing slowly-progressing visual changes and are left with few means of concretely demonstrating this to patients.

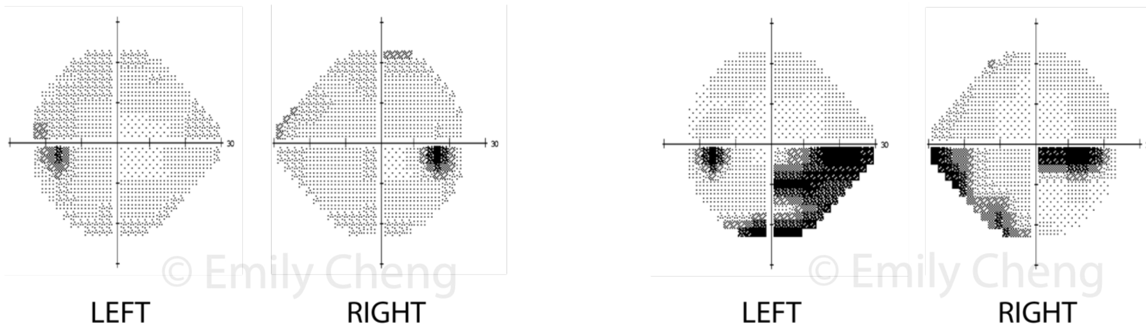


Figure 6. *Progressive HVF Images that Indicate Vision Loss for the Left and Right eye. Mild loss of the left and right eye depicted on the left, and increased levels of vision loss depicted on the right.*

Existing Visualizations and Limitations to Current Understanding

One solution to incentivize patient adherence to treatment is demonstrating visual examples of possible moderate or late-stage experiences that medication is working to prevent. However, existing visual materials that depict glaucoma are currently comprised of flat, 2D photos or illustrations with areas that are blacked or greyed out, or blurred. More concerning is the fact that most images are developed by an outsider's impression of visual loss caused by glaucoma. Ideally such images would be guided by patient-guided assessments that fully account for their true visual experience. As a result, many visualizations of glaucoma lack the specificity and full variability that a patient may suffer from, limiting the amount of information that can be accurately imparted to those learning about the disease.

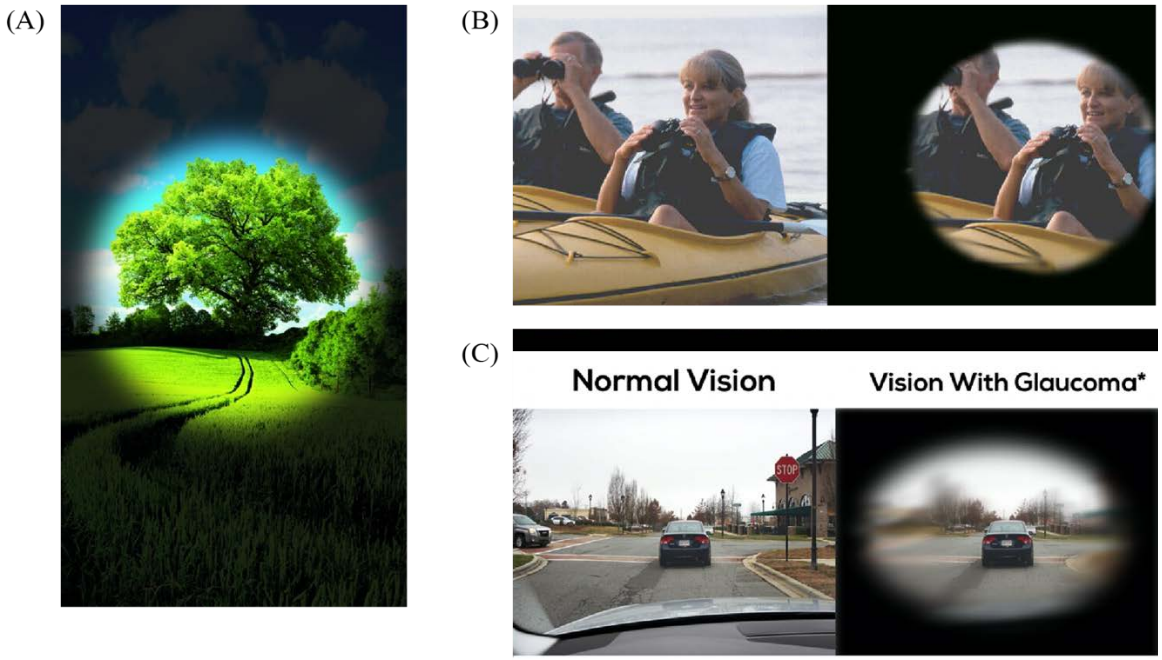


Figure 7. *Existing Sample Visual 2D Renders Demonstrating Limited Depiction Methodology.*

It is unknown how these images were derived and what methodology was used to develop these. Furthermore, it is unclear whether patients were interviewed in the process of developing the images.

Per our research, visualizations of glaucoma may not have yet been developed in a three-dimensional (3D) setting. This presents a tremendous learning opportunity for early-onset patients' understanding of how long-term quality of life (QOL) can be impacted by glaucoma vision loss. Simple tasks like perusing a grocery aisle for a specific item, doing laundry, cooking, or driving near a pedestrian walkway can become challenging or even life-threatening.

Visual field testing and optical coherence tomography attempt to quantify a worsening severity of disease, but do not directly speak to a patient's actual functional deficits. This is because these tests either capture structural features of the eye or simple visual response elements which are a very crude representation of what the patient sees.

HVFs can confirm diagnosis, but as many as 30-50% of retinal ganglion cells may be lost before being able to be identified in a visual field test (Weinreb 2014). OCT is most effective at diagnosing glaucoma and providing information at early stages of the disease. It is quite limited in its ability to judge progression of the disease, especially in moderate to severe stages (Ramulu 2017). Therefore, both tests reach a point at which they no longer provide useful information about disease severity. Ophthalmologists must then solely implement their care based on patient symptoms, which can lead to inconsistent interpretations and error-prone clinical treatment decisions (Ramulu 2020). The tests themselves therefore lack in specificity to help patients understand their own disease severity.

Virtual Reality and its Role in Ophthalmology

Use of Virtual Reality (VR)as a technologically advanced visualization tool that is rapidly expanding use within the medical field. It can be a particularly elucidating tool when applied to ocular diseases as it can be used to simulate many visual field loss patterns as well as provide a unique window to firsthand patient experiences that are otherwise difficult to communicate. In recreating patient experienced symptoms, VR users can not only visualize the effect of the condition but can also now experience the influence this has in navigating through a multi-dimensional space while performing certain tasks. Users can thus form a more informed opinion on the potential impact diseases such as glaucoma can have on activities of daily living (ADL) and QOL.

This research explores how VR visualizations can be applied to better understand glaucoma from the patient's perspective. If successful, this can then serve as a basis for further expansion into other ocular conditions.

Unity Game Development Software

Unity (Unity Technologies, San Francisco, CA) is game development engine that supports multiple distribution platforms (i.e. mobile, console, multi-player online, VR). It can be used to create two-dimensional, three-dimensional, virtual reality, and augmented reality simulations or experiences.

Educational Goals and Target Audience

The primary intent of this research is to provide an informational tool for newly diagnosed glaucoma or at-risk patients, whose adherence to early-stage medication regimens can greatly impact the trajectory of their disease. Patients should be able to experience, at some level, what their condition may become if it were to worsen. It is hoped this tool can serve as a method of encouraging consent to early intervention and incentivize adherence to medication protocol.

The application can also serve as a useful resource to secondary audiences like patient family members, ophthalmologists, or other related healthcare professionals. A better understanding of the patient experience of vision loss can help clinicians provide more compassionate care, while also allowing family members more empathetic insight to providing support.

Research Objectives

This research first aims to accurately depict the visual condition of several patients with glaucoma through the use of an IRB approved in-person and remote interview format using a standardized visual assessment methodology that addresses multiple variables, to systematically capture patient descriptions of their disease.

These data will then be used to develop a virtual reality (VR) application containing 3 learning modules. The **Live-Camera Module** simulates visually reported patient glaucoma conditions in real time through a live camera feed. A second **Search Task Module** applies the glaucoma vision as a filter in a timed search task within a home setting that engages the user and forces them to consider how vision loss can affect activities of daily living. Finally, a **Patient Education Module** provides hands-on, interactive 3D models and educational videos on the different types of glaucoma as well multiple types of exams used to quantify disease progression. The temporal nature with which each exam is administered and what specifically they help identify will be addressed in this module as well.

Materials and Methods

The planning and development of this VR application involved planning meetings with our subject matter expert (SME) team members. It was agreed upon to first prioritize developing accurate patient-specific renderings of glaucoma vision loss. This would be done through a standardized patient interview and assessment methodology. The next priority was to then import and image representing areas of vision loss and distortion (henceforth referred to as a "loss/distortion mask or mask") into a virtual reality setting with a live camera and search task simulation modules. Afterwards the supporting assets such as 3D models were developed. User interface design, and texturing within the search task and patient education modules were to be developed as time allows. Workflows for this research proceeded as follows:

Literature Search, Collecting Reference

Several existing studies were referenced in discussion with the SME team to establish the baseline of what is known and what remains to be understood in regards to creating visualizations of a patient's experience with glaucoma. Based on this, the overall established objective was to build a VR based application. A flowchart for the VR application is included here (refer to Figures 117A-D in the Results section).

The SME team provided unpublished manuscripts on patient reported symptoms and common terminology which were referenced in order to develop the adequate a visual field assessment tool needed for this research. The SME group also provided different types of visual exams (HVFs and OCTs) that were also used to develop patient education material as well as provide supplementary knowledge necessary to administer the developed visual field assessments to the test subjects within this study. Sample anonymized 30-2 HVFs were provided in order to develop quantifiable methods for documenting disease progression and visual loss. Sample OCTs were also provided as reference to augment understanding of the effects of retinal ganglion cell degeneration in glaucoma and how it is depicted within the eye. Further information on ophthalmological anatomy was gathered as reference material for the development of visual assets for the virtual reality application.

Software and Equipment

The following hardware/equipment and software was necessary in order to develop the assets and produce the simulation presented within this thesis (refer to Table 1). The VIVE Enterprise HTC VIVE Pro Eye Headset (New York, NY), along with two controllers and base station sensors, was used as the primary virtual reality tool that implements novel eye-tracking technology. An i7 MSI Gaming Laptop was used to connect the VR headset and run the game engine required to build the VR application. An HDMI mini-display port to mini-display port cable was an adapter that connects the Pro Eye with the laptop. A 38″ LG Monitor was used to administer patient visual field assessments during their initial interview.

Zoom Video Communications Zoom (San Jose, CA) was used to connect with patients remotely in order to conduct interviews. Adobe Photoshop CC 2021 (San Jose, CA) was used to develop the patient visual field assessment methodology, perform live-edits during the patient interview, produce patient glaucoma distortions visual loss/distortion masks, and develop VR and animation assets. Adobe Illustrator CC 2021 (San Jose, CA) was used to develop sprites for the VR application user interface. Maxon Cinema 4D v.R21 software (Friedrichsdorf, Germany) and Pixologic ZBrush v.2021.5.1 (Los Angeles, CA) were used to 3D sculpt patient education 3D models that could be exported with multiple material maps and imported into the VR interfaces. Adobe After Effects CC 2021 (San Jose, CA) was used to develop an introductory patient education animation to be shown within the VR space. Blender Foundations Blender 2.91.2 (Amsterdam, Netherlands) was used to develop 3D models for the simulated room environment for search tasks as well as the main page backdrop.

Unity Technologies Unity © 2019 (San Francisco, CA) was used to build all virtual reality scene and script simulations and interactivity for the 3D models. Software development kits needed to be installed into Unity in order to successfully implement the eye tracking feature in the HTC VIVE. The SRanipal SDK tracks the user's eye and lip movements (VIVE Pro Eye tracking sensors). Tobii XR SDK was used to allow the VR device agnostic access to eye tracking data, and expands upon the functionality of the SRanipal SDK. To access the front facing camera on the VR headset, VIVE SRWorks SDK was installed to provide further information on depth, spatial mapping, and live interaction and occlusion with virtual objects.

Software	Equipment
Pixologic ZBrush 2020	HTC VIVE Pro Eye – headset, controllers, base stations
Adobe Photoshop CC 2021	38" LG Monitor
Adobe Illustrator CC 2021	I7 MSI Gaming Laptop
Adobe After Effects CC 2021	Wacom Intuos Pro Pen & Touch medium
Adobe Media Encoder CC 2021	HDMI mini-display port to mini-display port cable
Blender 2.91.2	ROG Spatha Gaming mouse
Maxon Cinema 4D Studio R21	Apple iMac 2017
Unity © 2019	
VIVE SRanipal SDK	
Tobii XR SDK	
SR Works SDK	
Zoom	

Table 1. *Hardware and Software Used to Implement this Research.*

Project Phases

The overall development of this project took place in two phases: Phase 1 involved conducting patient interviews, followed by Phase 2 VR which focused on the VR application development process. The objective of the interview process was to methodically capture, using a standardized method, the kinds of visual perception glaucoma patients experience. The VR application was then developed to depict this experience, while also including teaching opportunities that allow the user gain new insight on how late-stage glaucoma occurs and impacts daily living.

Phase 1: Development of Patient Visual Distortions

To achieve a standardized methodology for assessment, multiple types of existing visual grids were referenced (i.e. Amsler grid, HVF). Different activities comprising daily living scenarios were considered as potential background images to assess visual field loss.

Over several meetings with the SME team, it was agreed that our assessment methodology would involve first presenting an image of a "scene" with a grid pattern superimposed on it. Several default distortions of the scene were created ahead of time using Photoshop filters and brushes to prompt discussion with the test subjects. The distortions are different types of visual impairments commonly experienced by patients with glaucoma. Live edits to those distortions were then made real-time based on patient feedback.

Choosing the Scene

Meetings were held with the SME team to discuss typical scenarios in which the impact of glaucoma is most apparent in affecting ADL and QOL. Some examples included (i) driving on a freeway or on a street where pedestrians may cross (ii) shopping in a grocery store with an abundance of items in the aisles (iii) searching for an object in a cluttered area, like a pantry. Ultimately, it was decided that an effective testing image would need to provide extensive detail within all visual field quadrants. The chosen image that effectively met all these objectives was a grocery store aisle. Thus, a local supermarket grocery aisle was captured using an iPhone, and saved as a JPG file (Figure 8). This scene showed extensive products throughout the field of view.

Figure 8. *Captured iPhone Image of Local Grocery Store Aisle.*

Development of the Visual Assessment Grids

The final visual assessment grid that was superimposed on the image went through several iterations. Initially, multiple existing visual grids were considered. The Amsler grid, which tests for macular degeneration and central field loss, provided a good starting point. The lines within the Amsler grid may be faint of missing in the presence of a visual field defect, and thus provided a potential avenue with which the research assessment grid could be referenced (Figure 9). The Humphrey Visual Field test also tests for regionality of visual field loss and points are oriented every six degrees along the x and y coordinates.

The idea was to implement a grid pattern, or something with uniformity that can help identify areas of distortion.

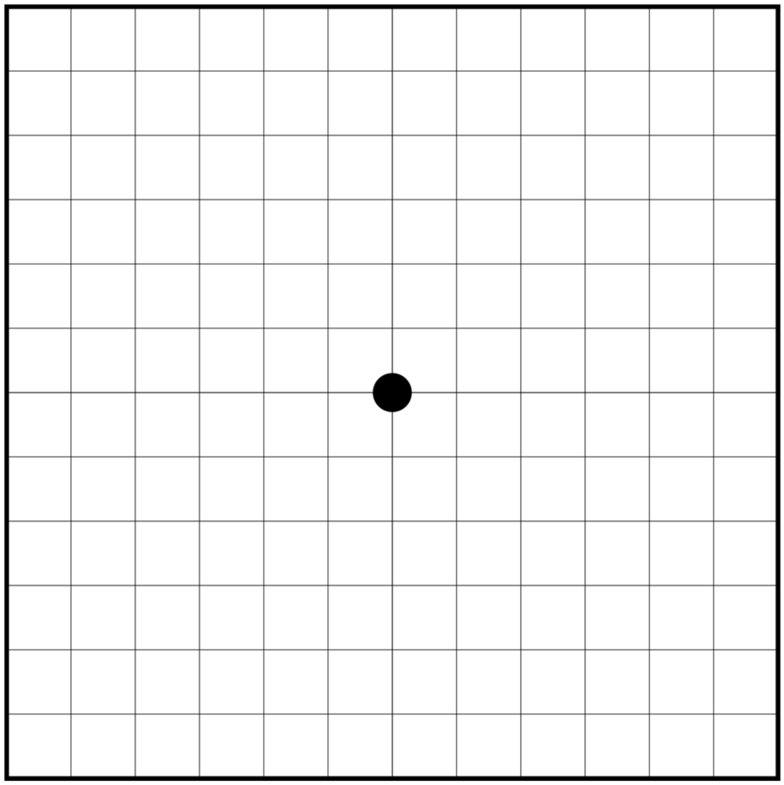


Figure 9. *Example Amsler Grid.*

Initial designs, developed with Adobe Illustrator CC 2020, included a checkerboard pattern, with labeled with colors, numbers, and letters to allow for the patient to identify areas of distortion (Figure 10). The grid then evolved to one that matches the HVF exam test result, where blind spots and peripheral areas not being tested are blacked out.

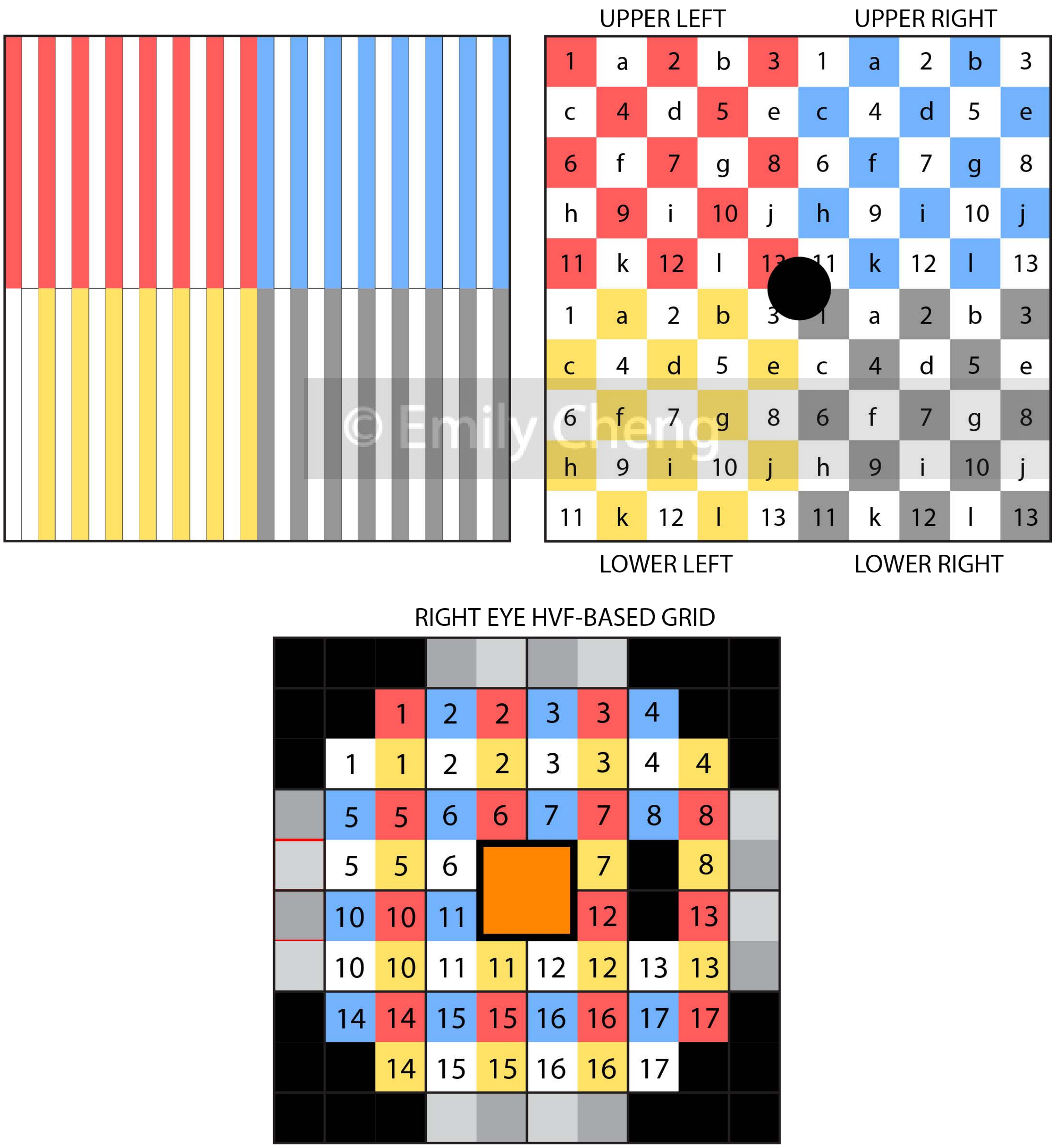


Figure 10. *Initial Sample Grids Variations.*

These initial renditions suffered from business and clutter, which when superimposed on the scene, hinders the viewer from processing the scene itself. Blacking out the areas that weren't tested by HVF also was counterintuitive to the idea of aiming to approach or understand the patient condition uniquely. Therefore, the blind spot and black areas were eliminated, the unit count was reduced to a finer grid, and the grid itself was generously expanded to cover as much peripheral vision as possible. Larger unit squares with regionality labels were placed over the finer units to allow for broad regional identification of distortions before further dissecting their compositions (Figure 11).

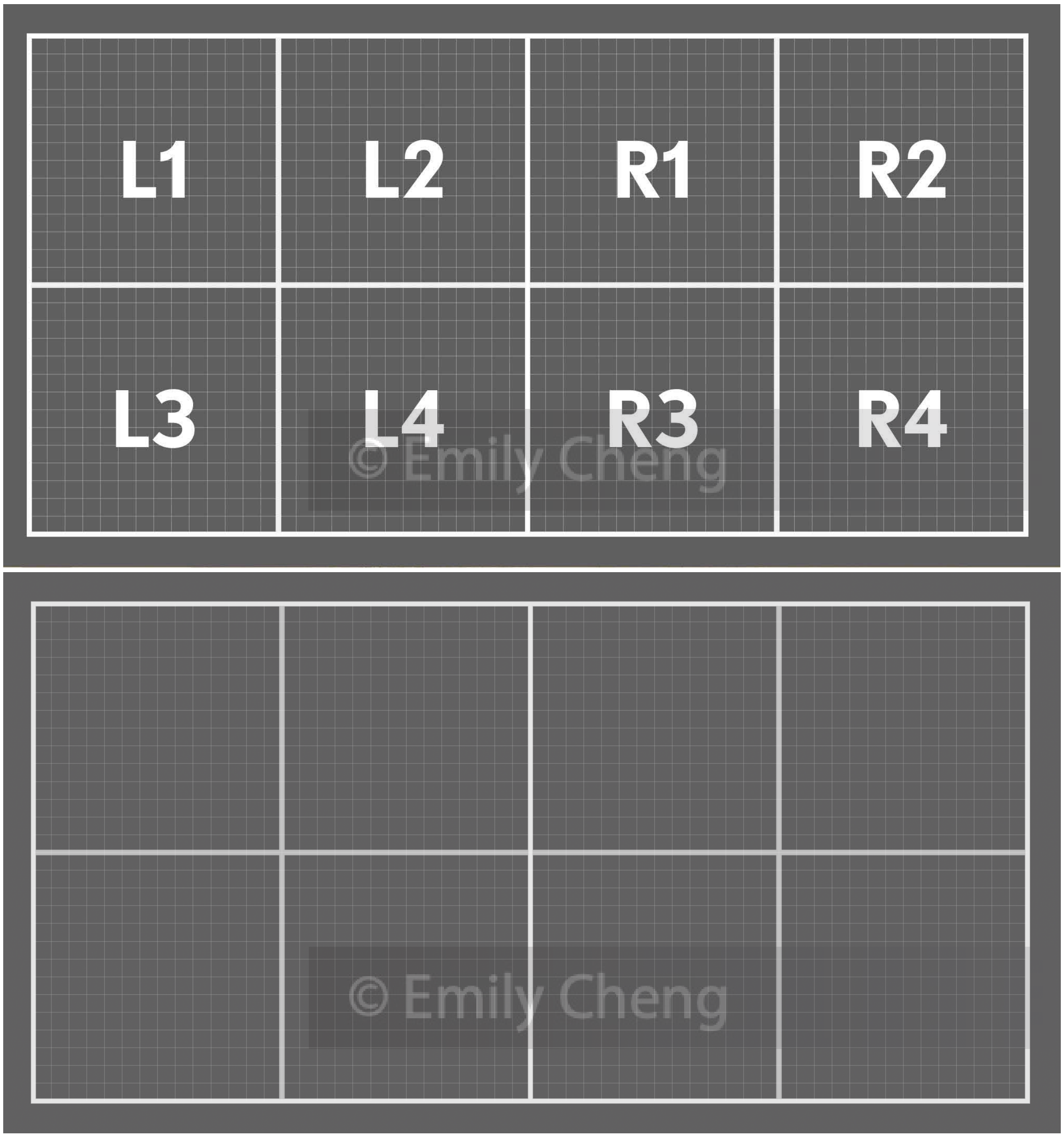


Figure 11. *Final Grid with (Top) and without (Bottom) Broad Regional Identifiers. Superimposed on a grey background for visibility.*

Development of the Filters and Distortions

According to prior unpublished research conducted by the SME team, the most commonly reported descriptors of what patients see when their condition is apparent include better vision in one eye, blurriness, cloudiness, glare, sensitivity to light, floaters, as well as halos. In addition, patients commonly reported having missing patches of vision, as well as little peripheral vision (Hu 2014 & Ramulu 2020) (see Table 2). These descriptors seemed to apply across a wide variance of visual field (VF) damage, and that the frequency of peripheral vision loss, missing patches of vision, and cloudiness are significant.

Photoshop was used to reproduce these commonly reported visual deficits or distortions. Each deficit was constructed within a Photoshop Layer using various brushes. The distortions were then presented later during the visual assessment as conversation starters for patients to compare to their own condition. Particular variables we wanted to address in developing these filters included how to present degrees of intensity of the filter and how to bring up regionality of each filter. One trait of glaucoma that was not addressed in this questionnaire is the temporal variation the disease has on patients.

Common Descriptors of Visual Distortions	Filter Applied in Visual Assessment Tool
Blurriness	
Cloudiness	X
Glare	X
Sensitivity to light	
Floaters	
Halos	
Missing Patches of Vision	X
Peripheral Vision	X

Table 2. *Common Descriptors of Patient Visual Distortions Used by Patients.*

To construct each filter, a separate layer was created within Photoshop. Various brushes with different tones and opacities were used to create an effect that mimics the description. The dimensions of each distortion were consistent with the dimensions of the visual assessment grid that will be superimposed on the scene image. The resulting distortions make up 5 separate layers within a Photoshop file, and have the flexibility of being presented at a range of opacities to best reflect the intensity of patient distortion.

Blur and contrast distortions were also addressed as modifiable variables. For blurs, the scene image was duplicated, converted into a Smart Object, and then modified via a Gaussian blur. The level of blur could then be adjusted until it was verified to be close to what a patient viewed with their impaired eye. With the image set as a Smart Object, contrast also became an accessible, adjustable filter which could then be tailored according to patient feedback.

Compiling the Patient Visual Assessment Tool

To fully compile the patient visual assessment tool, the scene image, assessment grid, and each layer of pre-made distortions were combined into one Photoshop file. To fully account for as much peripheral vision as possible, the background image was expanded to a size where the visual assessment grid could be tiled on a 3x3 area.

The completed filter layers are labeled as distortions 1-5, each of which are covered by an inverted mask. Only in the instance where the patient pointed out they see a distortion would the masked be filled in with white to reveal the underlying distortion.

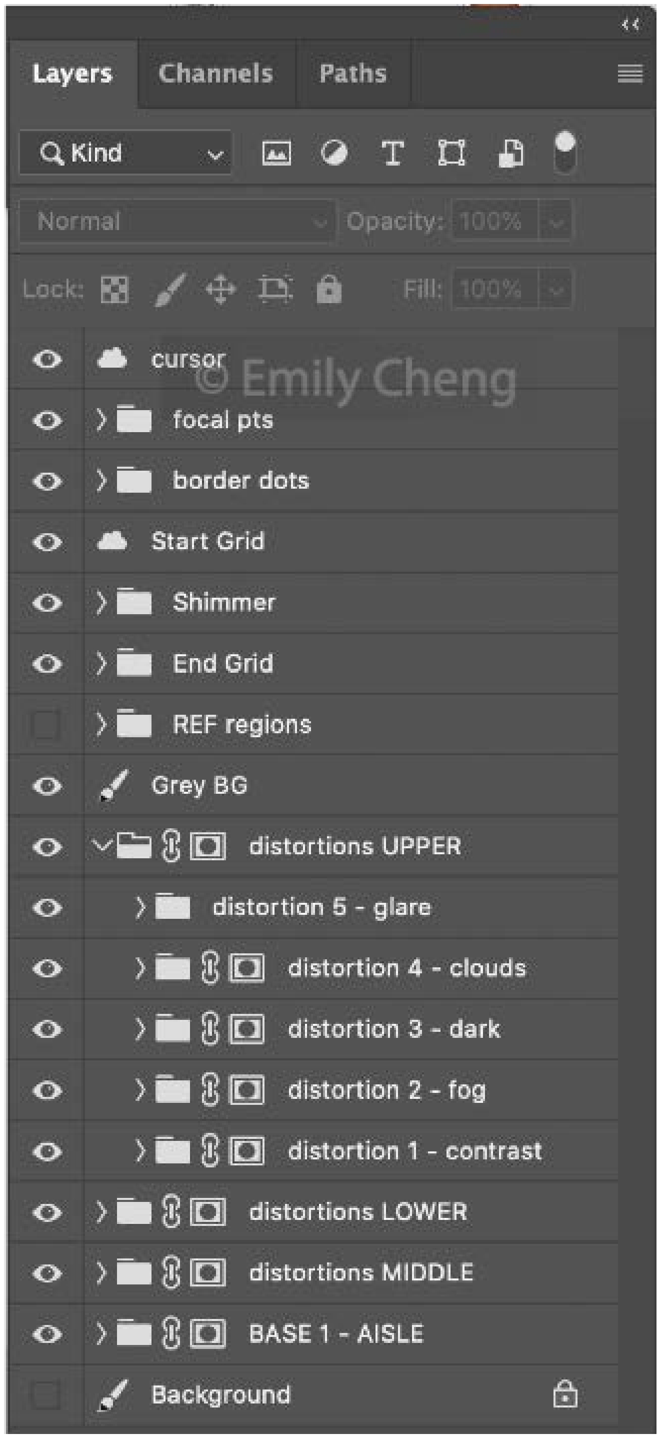


Figure 12. *Layer File of Distortion with Masks.*

Each "tile" of visual grid contains its own accompanying set of distortion layers to provide increased control of regionality of the distortions. The file was presented with the surface area of one grid tile at a time, and was only moved around to include the other grids when analyzing far periphery.

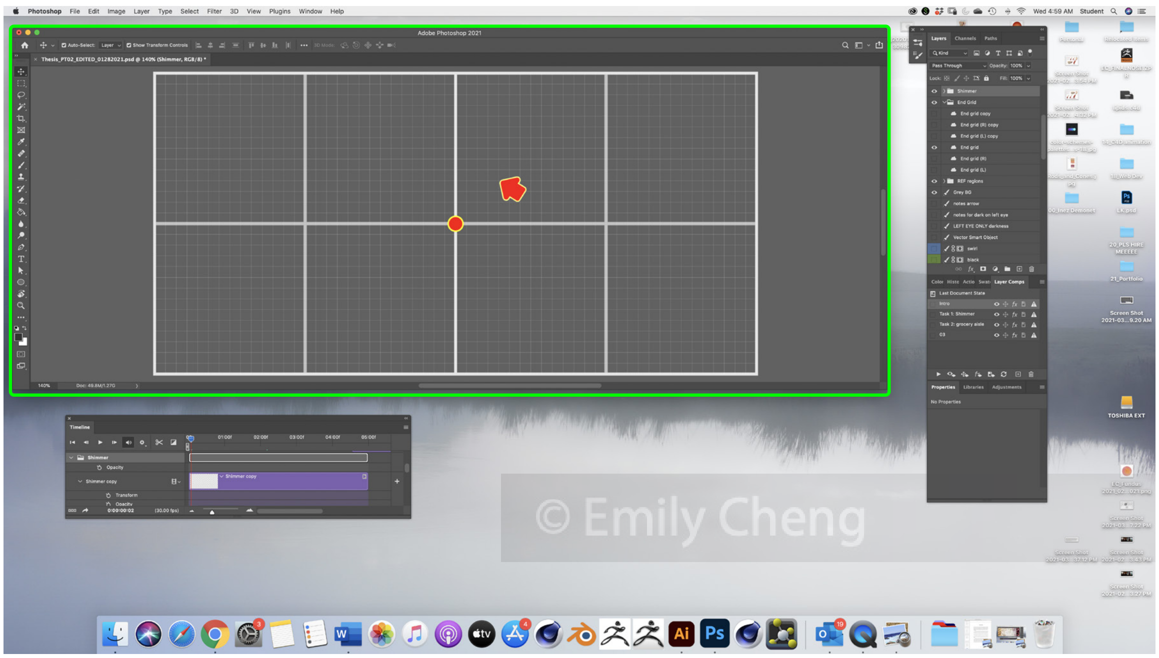


Figure 13. Screenshot of File Upon Initial Presentation. Area highlighted in green is screen shared through Zoom. Text not intended to be read.

Several additional visual elements were created and utilized to guide the patient's eyesight around the assessment document. Each assessment document contained a **focal point** – a bright red dot in the center of the questionnaire file. The dot was colored so that it was still very visible relative to the background in colorblind mode (Figure 119). When assessing the composition of the distortions within the patient's peripheral view, the focal point was moved to sides of the document, and the patient was asked to remain focused on the point.

A **bright red, yellow outlined cursor** was also used to move around the questionnaire image to allow the patient to easily identify the region of the image being discussed. The arrow was moved in circles, so that the patient can point out when they detect movement, even if they cannot see the arrow itself. Information on what the kind of information the patient was able to distinguish – movement, color, movement only but not color, or both movement and color – were documented in the process (Figure 14).

Labels L1-4, R1-4 were also placed in 8 larger squares over the assessment grid to clearly display the left and right quadrants of the focal point. This was created in a layer that could be easily turned on and off when necessary.

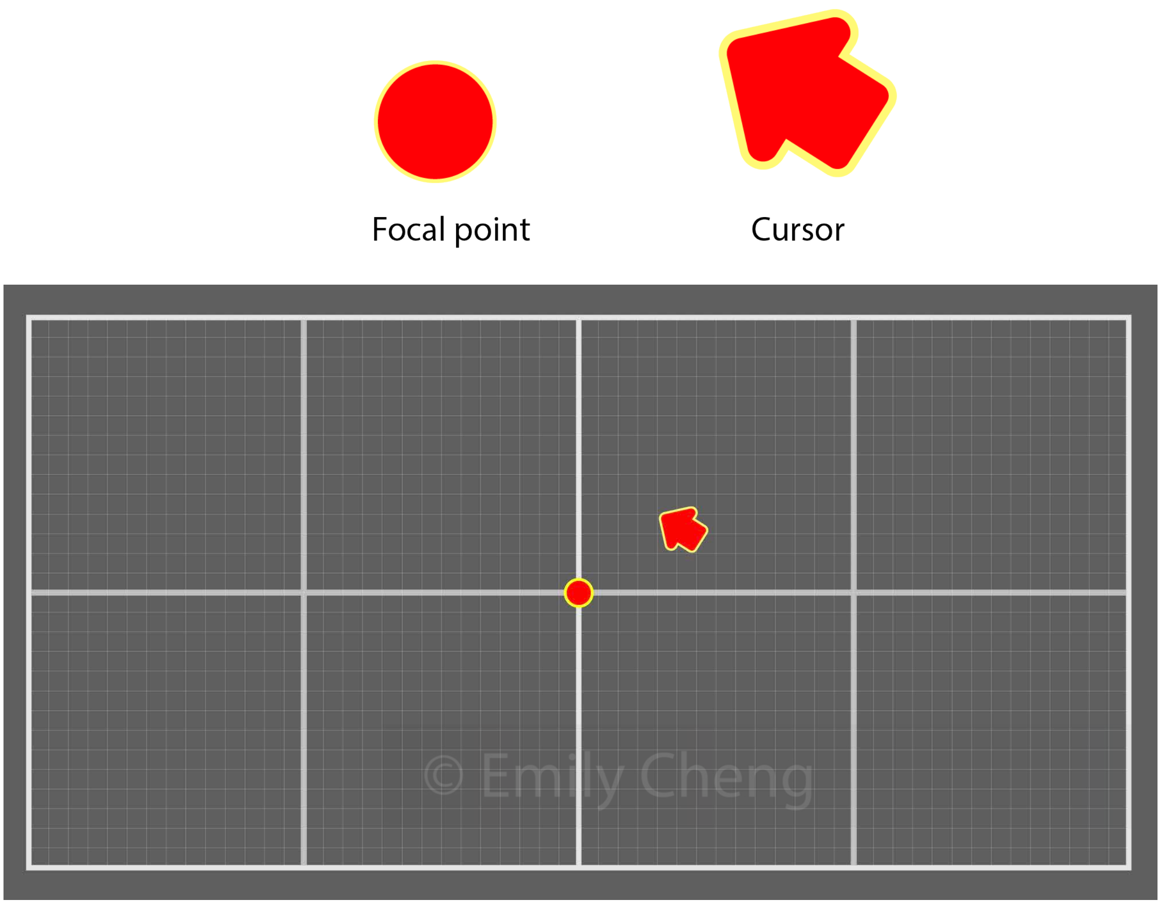


Figure 14. *Important Visual Elements Placed on Assessment Grid.*

A standardized **shimmering scene** was also developed within the file to provide a uniform pattern with which the patient can easily identify areas that differ from the rest of their vision. The shimmer texture is created through two separate, masked layers. The degree of masking is animated by setting two keyframes at different timepoints in Photoshop's timeline feature. The transition between the frames was then scrolled manually to produce the looping shimmering effect without taxing computer memory, while also permitting edits when the patient identifies areas of distortion (Figure 15).

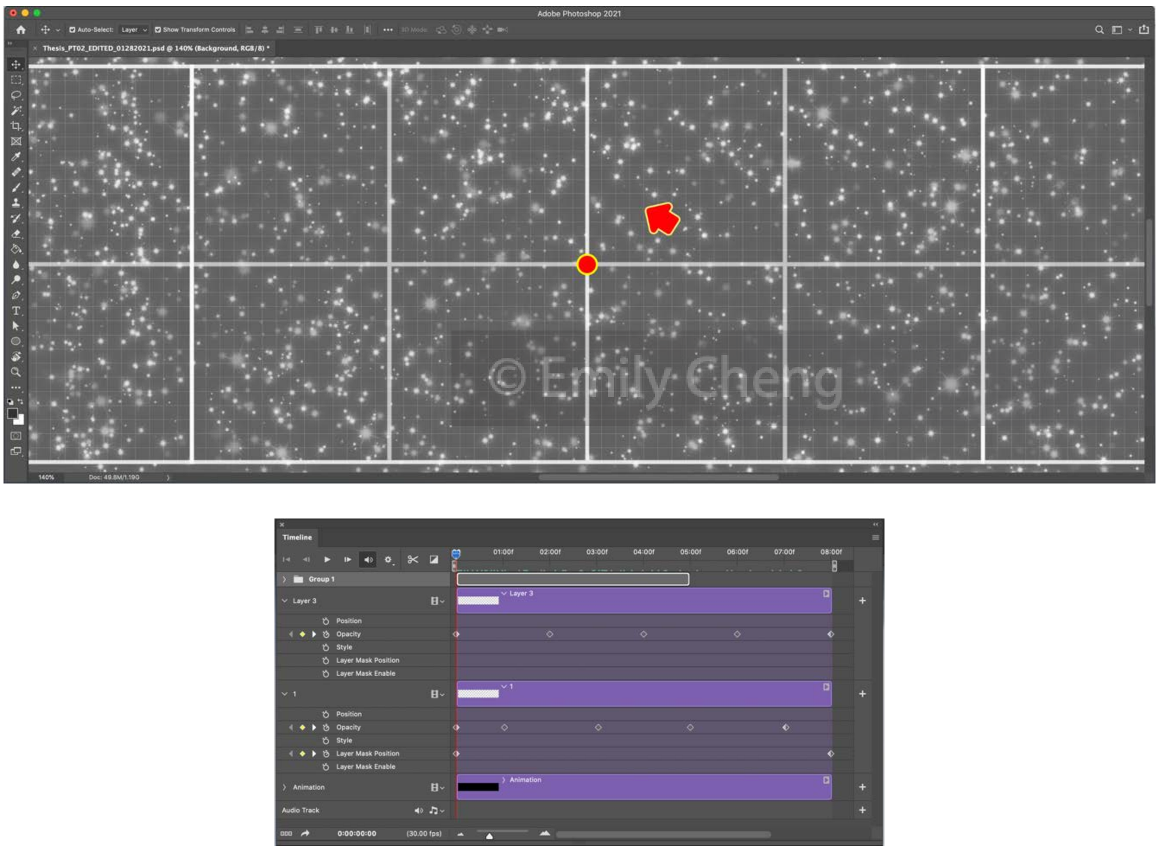


Figure 15. *Screenshots of Shimmer Animation Timeline with Corresponding Visual Screen Shared through Zoom. Text not intended to be read.*

Presenting the Patient Visual Assessment Tool

A script and protocol were developed to streamline administering the patient visual assessment tool script (*refer to Appendix A*). Previous HVF and OCT test results for each patient were also obtained beforehand in order to provide reference that may help guide administration of the visual assessment tool. The patient first received an introduction about the study. Instructions on allowing the patient to switch between their normal and impaired eyes were provided during this introductory phase. The patients were then walked through the important elements that require their attention within the Photoshop file. This included the labelled assessment grid with regional syntax, the focal point, as well as the red cursor.

After confirmation that the patient had familiarized themselves with these elements, the "shimmering scene" was brought up as the first task of the interview. We communicated to the patient that the objective of this task is to identify the regions of distortion, with which the compositional details will be addressed later. The patient was first asked with viewing the shimmer with their normal eye and an eye-patch placed over their impaired eye. When they were ready, they were instructed to switch their eye-patch, and to view the image with their impaired eye. The patient was free to switch off viewing the image between either eye for as many times as they needed in order to identify the regions with distortions. These identified regions were marked and then unmasked within the Photoshop file for further exploration in the second task. The results were accepted regardless of how much they agreed or differed from the HVF results. However, the HVF results were referenced before performing the visual assessment. Upon completion of the first task, the second scene of the grocery aisle, with the assessment grid and multiple pre-generated distortions, were shown.

To allow easier workflow, the necessary layers for each stage of the interview process were compiled into "Layer Compositions" within Photoshop. The first layer composition had only the cursor, focal point, grid labels, and visual assessment grid layers visible. The second composition introduced the shimmering scene. The final composition replaced the shimmering scene with the grocery aisle image and distortion masks (which do not appear visible due to masking). (Figure 16). The primary purpose of the initial session was to document and indicate regionality of the distortions while also obtaining a general tonal composition of the obstruction.

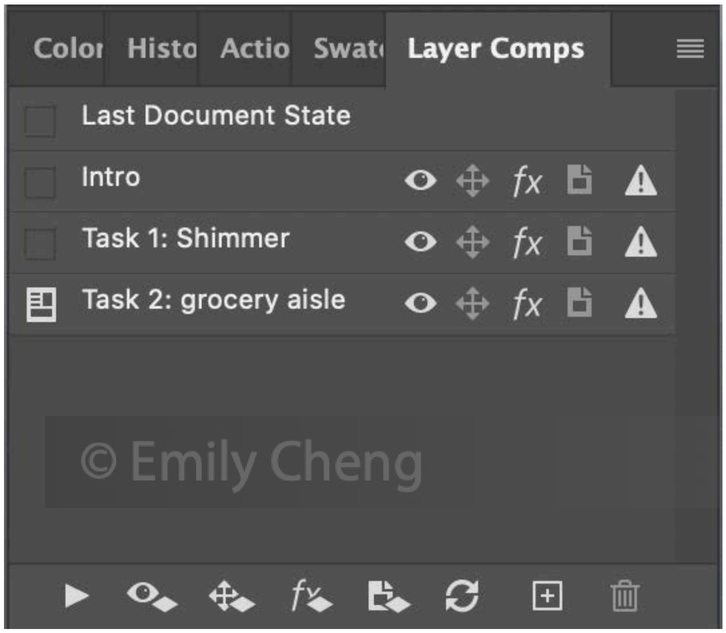


Figure 16. *Layer Compositions Hierarchy in the Final Assessment Grid Stages.*

Patient Interviews

Recruitment

Patients were recruited based on a preset criteria of visual field damage through an IRB- approved protocol. All patients had unilateral glaucoma, allowing them one unaffected eye that acts as a visual control. This allows them to identify the functional differences between the normal image and the distortions they might see on the image with their impaired eye.

Recruitment was conducted over the phone – patients meeting the exclusionary criteria who are also scheduled to visit clinic for a separate appointment were sought out and asked if they were willing to participate before or after their clinic visit. Consent from the patient was provided and all protocols were in accordance to the IRB approved research protocol which met HIPAA guidelines.

Initial Patient Interview Set-up

The first interview session was held with each patient either before or after their on-site clinic visit. A curved 38” LG desktop monitor was purchased to project the questionnaire over a larger set of dimensions. The curvature of the monitor allowed for peripheral points to have a more equidistant relationship and could prevent distortion relative to the distance to the eye. The assessment image was shown remotely through the Zoom share screen feature (Figure 13).

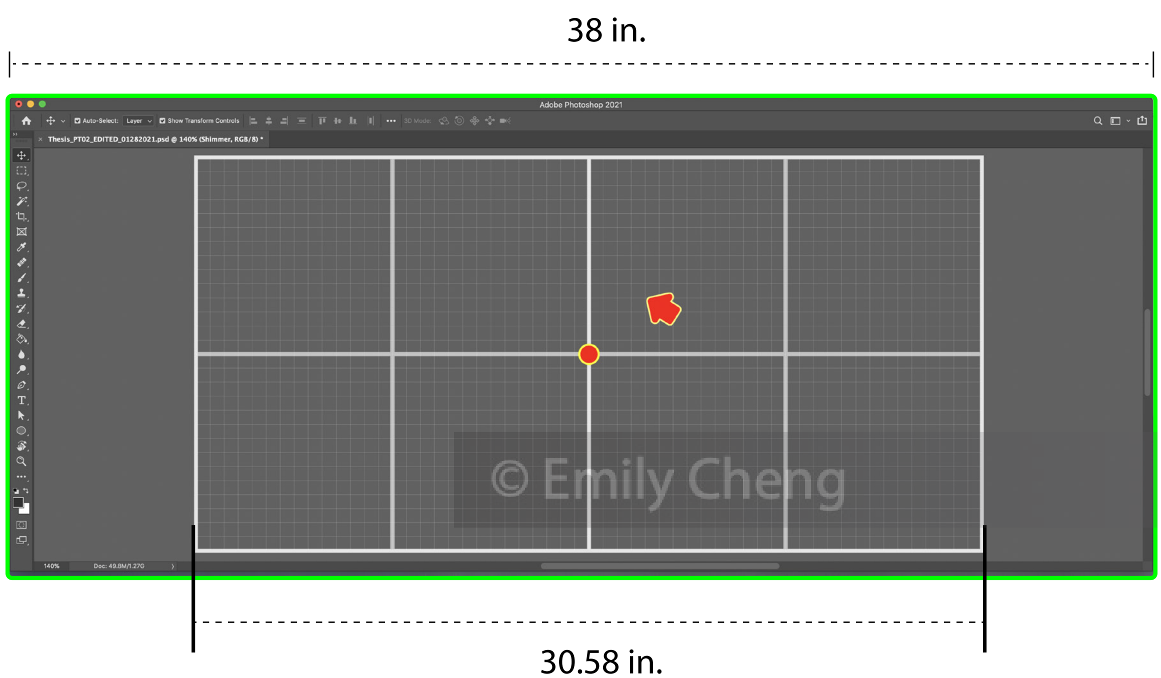


Figure 17. *Final Dimensions of Image Projected onto the Monitor in Clinic. Text not intended to be read.*

To determine the best distance at which patients should sit from the monitor, the initial angle of peripheral view was first identified. Since the standard HVF test typically assesses vision within 30 degrees of fixation, and 60 degrees within fixation is determined to be the upper end of the mid peripheral measure, it was determined 70 degrees from fixation to be an appropriate value for assessment. The distance was then back calculated using the projected distance of the two furthest points on the visual assessment grid with the following equation:

$$\tan y = \frac{x}{d}$$

y = degrees of vision.
x = distance in centimeters between two dots on visual assessment grid.
d = distance in centimeters between the screen and the patient's eye.

Figure 18. *Equation Determining Distance at which Patient Sits from Screen.*

The two furthest points were measured to be 28.8 inches or 73cm apart. The distance equation would therefore be:

$$d(\text{cm}) = \frac{73\text{cm}}{\tan 70 \text{ deg}} = \mathbf{60\ cm}$$

The patient was therefore instructed to sit 60cm away from the desktop monitor (Figure 19).

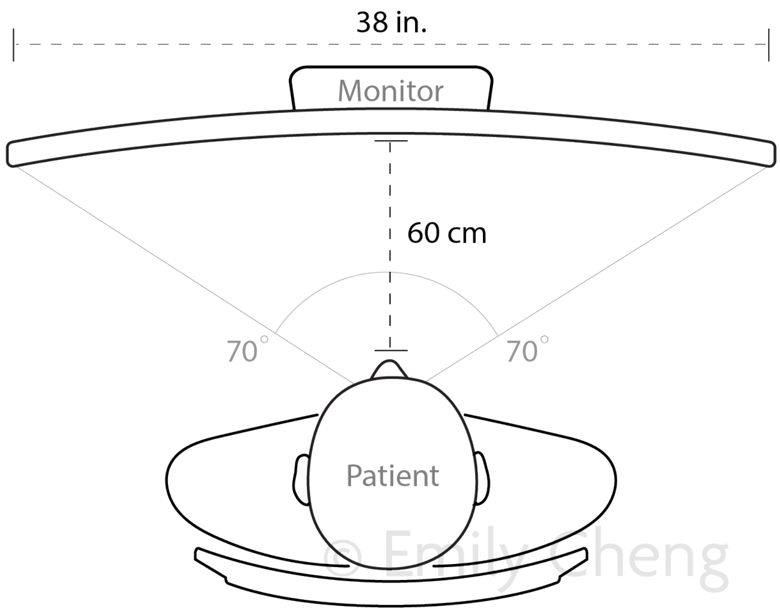


Figure 19. *Patient In-Clinic Set-up. The patient is situated 60 cm away from the 38″ monitor, allowing for 70 degrees of vision from the point of fixation per eye.*

Single use pirate eye patches were also provided for the patient to be able to properly switch between their normal and impaired eye for visual comparison during the study.

Post-Clinic Updates to Initial Vision Mask

Follow-up sessions with the patient were then conducted remotely via an online platform. The image was projected through the Share Screen function of Zoom and viewed through a patient's home display monitor. The patient was then asked to verify if the image generated based on their interview looked accurate or inaccurate. Regionality was not addressed during these sessions as the display dimensions varied due to use of at home monitors or tablets. It was determined that there are too many uncontrollable variables when working with patients outside of the clinic environment that make it difficult to assess the regionality in a standard manner. Modifications to the initially generated image were then made based on the feedback and incorporated into the final image.

Finalizing Patient Masks for Import into Virtual Reality

The representation of the patient's glaucoma vision mask thus produced contained tonal information with areas of vision loss represented as opaque, and areas of normal vision transparent. Because Photoshop does not allow for a blur effect to be applied to a transparent image, the blurred study image itself was saved into the mask, introducing some inconsistencies which will be discussed later. Once confirmed patients' visual assessment files were then saved in a .PNG file format. The size dimensions of the exported files were 19.2 inches x 9.807 in. These were saved at original size and later scaled within Unity. Import of the .PNG masks is discussed in Section 2 of the Materials & Methods.

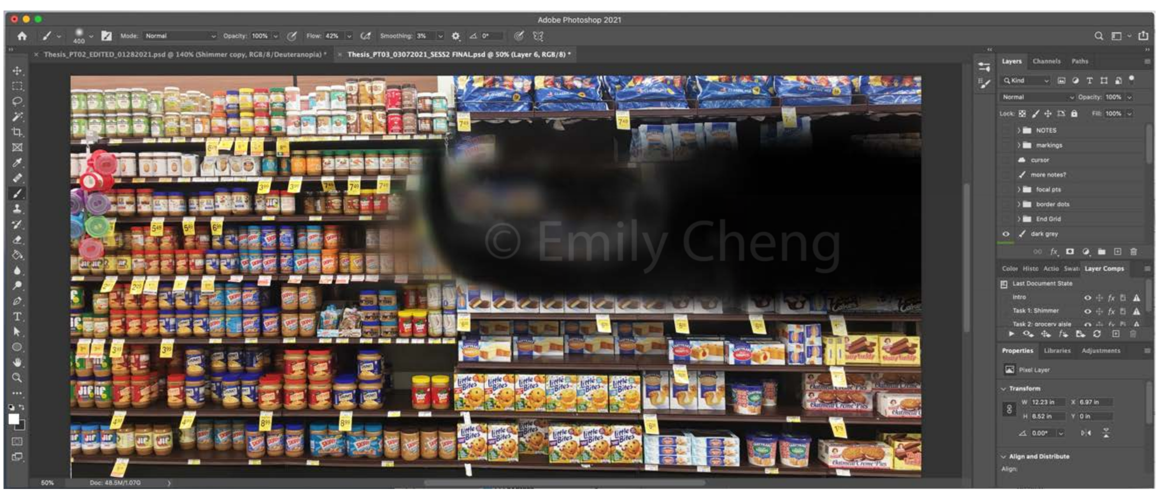


Figure 20. *Representative Image mask. Text not intended to be read.*

Section 2: Development of the Virtual Reality Application

The second part of this project served to depict the resulting data through virtual reality (VR) eye-tracking technology in order to demonstrate aspects of the disease in different settings. Executing this involved designing and developing a user interface, 3D modeling assets, and additional educational material to be imported within the VR space through Unity. These are outlined in detail in the following sections.

Understanding Unity Development Workflow

When using Unity to develop a VR based interface, several important concepts are necessary to understand the project development workflow. The process of building the Unity file or "project" occurs within a series of common editor windows:

1) **Scene View**- displays all of the objects placed within a portion of the project. One selects, manipulates, and modifies objects within the Scene view. A project or game can contain multiple scenes, each with their unique environment, arrangement of objects, and associated activities.
2) **Game View**– displays all of objects within your scene rendered from the point of view of a camera existing within that scene. It represents the real-time interface that the player interacts with.
3) **Inspector Window**– contains all of the components and properties of a selected object (such as scripts, sounds, and lights). It provides capabilities for functionally modifying those objects and their properties.

4) **Project Window**– this contains all of the files and assets associated with the application or game.

The specific building blocks used to build a project within the editor windows include:

1) **GameObject** - the default class for all entities placed within a Unity Scene. This includes directional light and cameras, all user interface components, environment assets, and more.
2) **Rigid Body Collider** – components that are added to two GameObjects to allow for collisions to occur
3) **Sprite** – is a 2D graphic object that are Assets in Projects.
4) **Canvas** – is an area in which all user interface (UI) components can be placed. This includes buttons, text elements. The canvas can be oriented as suited in 3D space.

Some relevant language that is incorporated into the C# scripts include:

1) Boolean (bool) - a variable that holds either a true or false value.
2) Float – used to define a variable with digits
3) Function – used to execute certain "blocks" of code
4) Public/private - variables that are accessed either only within (private) or outside of the class (public) with which they were defined.
5) If else statements – statements that execute an expression under specified conditions

Design of the User Interface

Three types of Unity scene user interfaces were developed for this project. The first was used as the main environment or "scene", which the user first encounters. The second was used with the "Live-camera" and "Search Task Simulator" modules. The final scene was used for the "Patient Education" module, to help the user navigate between different eye anatomy models and videos to learn more about glaucoma.

The process behind designing these interfaces occurred through sketch and rough draft renditions. Rough drafts were then brought into Illustrator to be refined (Figure 22). Once the aesthetic of the interface was finalized, each asset was exported as a .PNG file to be placed within the Unity game engine interface (Figure 21).

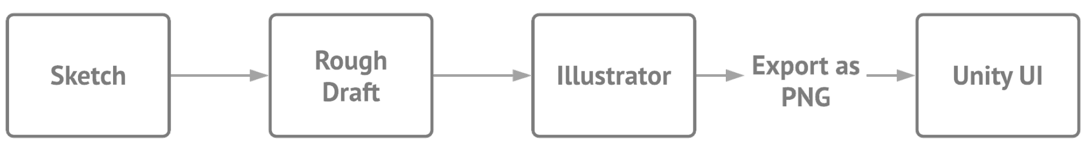


Figure 21. *Diagram of the Design Workflow*

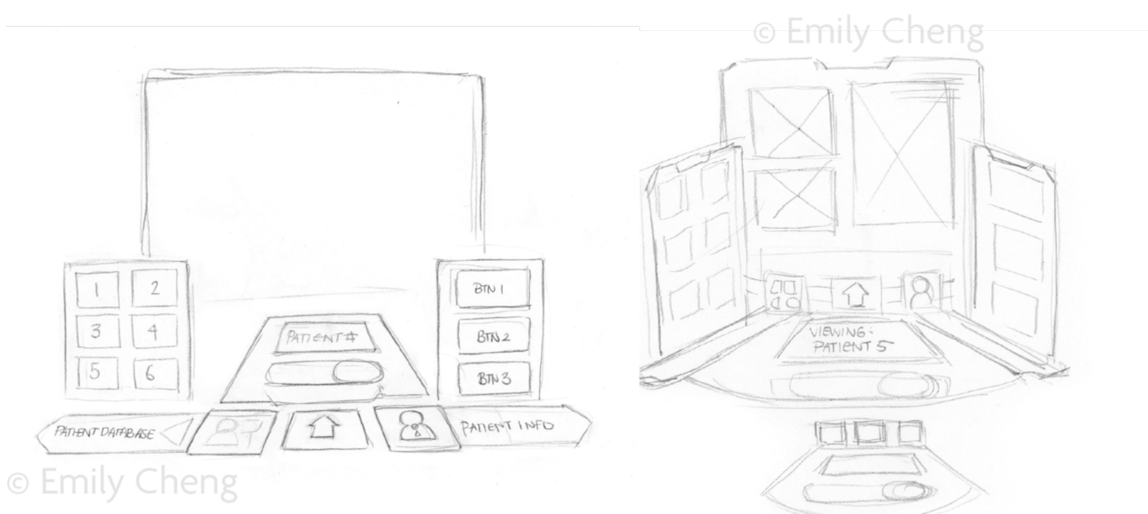


Figure 22. *Initial Rough Sketch Design of UI and Rough Storyboard*

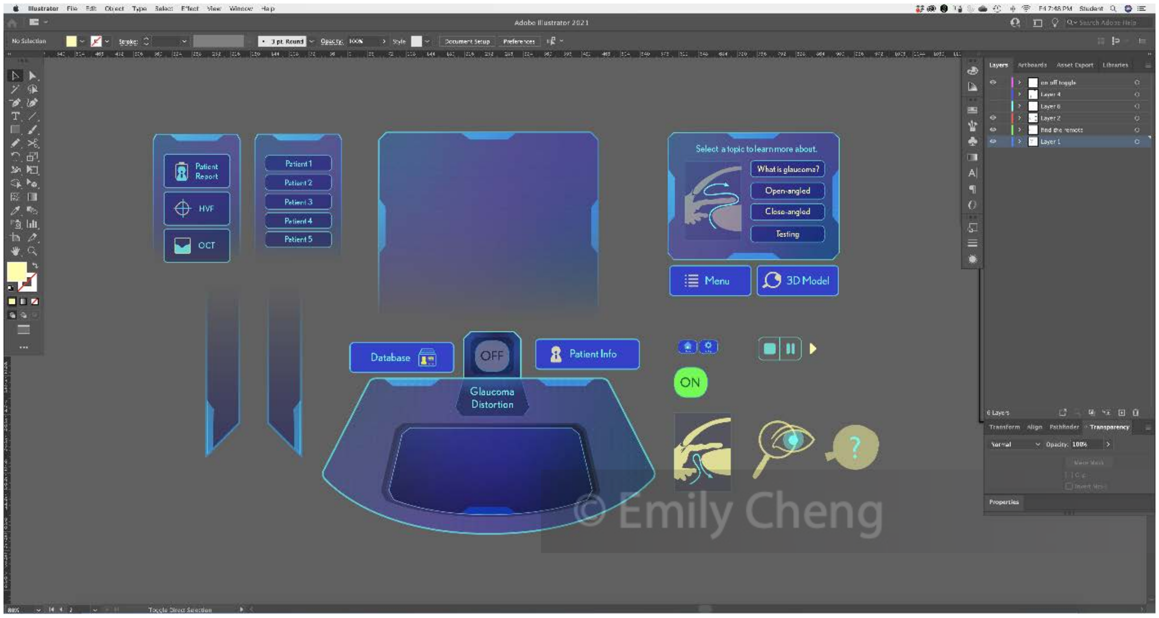


Figure 23. Flat Illustrator File Layout. Text not intended to be read.

Final PNGs were uploaded into Unity as 2D sprites, which could then be used as interface or image "panels" in the UI Canvas when building within the Unity interface (Figure 23).

Features of the Various User Interfaces

User Interface within the Main Scene

Users enter into a world where there are balls orbiting an eye. Each ball or "mini-orb" represents a module which the patient can explore (Figure 24). The modules are listed as follows: (i) Live camera module (ii) Search Task Simulator module (iii) Patient module and (iv) an About page.

Figure 24. *Rough Storyboard Concept of Main Scene. Text not intended to be read.*

User Interface within the Search Task Simulator and Live-Camera Modules

The user interfaces for both the Search Task Simulator and Live Camera modules follow a similar general structure. Both begin with instructional menu, which will prompt them to select a patient mask before accessing the main interface.

The live camera feature immediately utilizes the HTC VIVE front-facing camera. The initial user interface that appears with this scene will contain instructions on which patient to select, as well as instructions on the two accessible features the main interface contains. After selecting a filter, this instructional panel disappears and the base interface model with two accessible features, “Patient database” and “Patient info”, as well as an “ON” and “OFF” toggle will appear. The toggle is set to be “OFF” and both feature menus are collapsed by default. The user can press the patient database and patient info buttons to open submenus that allow them access to different patient filters as well as testing and clinical reports on those patients. The user has the ability to re-collapse each of these menu items.

The Search Task Simulator module uses a similar interface with the addition of a timed activity that requires unique user interface prompts prior. The user is first greeted with an instructional panel explaining the timed activity.

Users press "Begin" to move forward with the sequence and are then prompted to choose a specific patient vision distortion. Upon selection of the patient, the task begins and a scripted timer begins to countdown. Once the task is completed, or the user "exits" out of the task, the user gains access to the rest of the user interface that allows them to explore patient masks and information within the simulation space. Contrary to the initial state of the user interface within live-camera, the user interface within this scene will begin with all sub menus spread out, and the toggle button "ON".

"Home" and "Settings" buttons are made available on all user interface panels to allow the user to exit out of the module at their discretion.

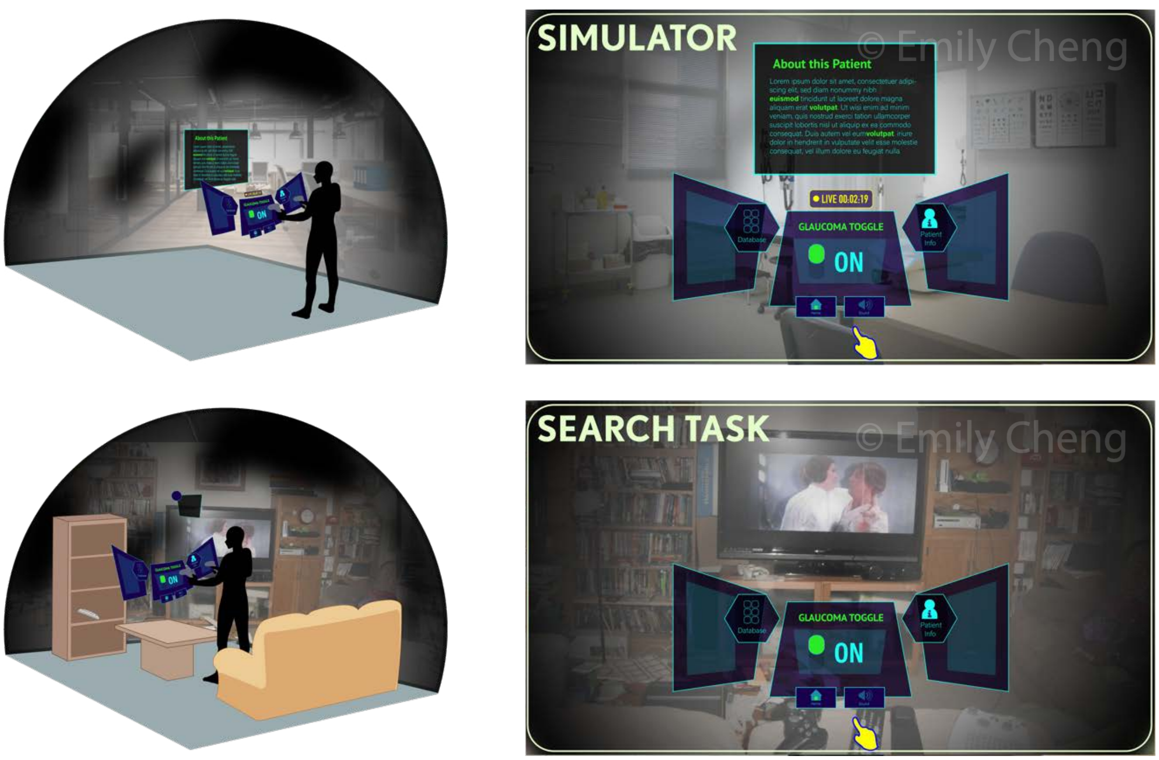


Figure 25. *Rough Storyboard Concept of Search Task UI. Text not intended to be read.*

User Interface within the Patient Education Modules

When the user selects the "patient education" button from the main page, a user interface menu for patient education materials appears within the same scene. The module prompts all of the main menu assets to disappear. Within the patient education UI menu, instructions prompting the user to select an educational animation along with buttons for each of those animations appear. After the topic of choice is selected, the screen is replaced by a second screen containing the educational animation along with pause and play controls. Stopping the animation brings the menu page back. A "Menu" button, "Home" button, and "Settings" buttons are available for the user to navigate between interfaces. Finally, a "3D Model" button initiates the appearance of a 3D model of the eye. The model has call out labels that indicate anatomical structures of interest.

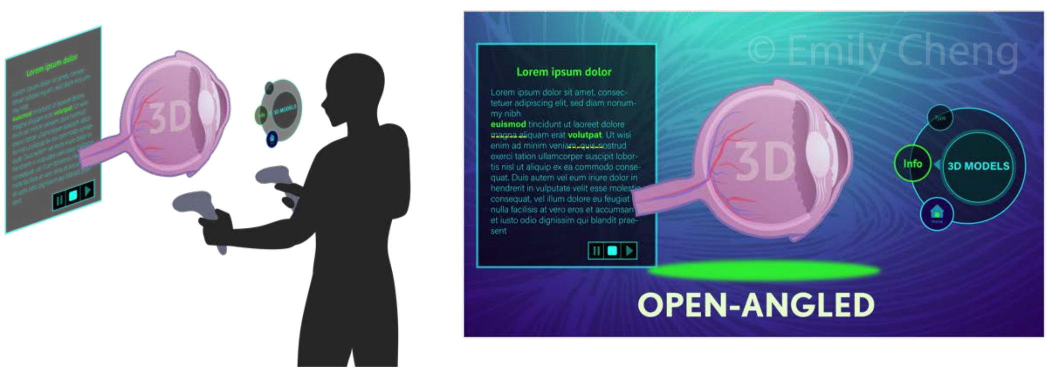


Figure 26. *Rough Storyboard Concept of Patient Education Modules. Text not intended to be read.*

Development of VR User Interface within Unity3D

Multiple Unity add-ons and plug-ins were installed in order to make user interface interactivity functional. This primarily allows making objects within the application interactable when using the VR controllers.

Steam VR and VIVE Input Utility

SteamVR was first installed through the Unity Asset Store in order to access a separate plug-in called **VIVE Input Utility**. VIVE Input Utility implements Vive device interactivity within the Unity3D game engine. Once installed, “ViveRig” can be accessed in the “Prefabs” folder of the “Vive Input Utility” folder in the Project Menu and placed within the hierarchy in the scene.

The primary feature of interest of the Input Utility used within this research project was the “**Canvas Raycast Target**” script. This component was added onto every interface asset so that it is recognizable by the VIVE controllers.

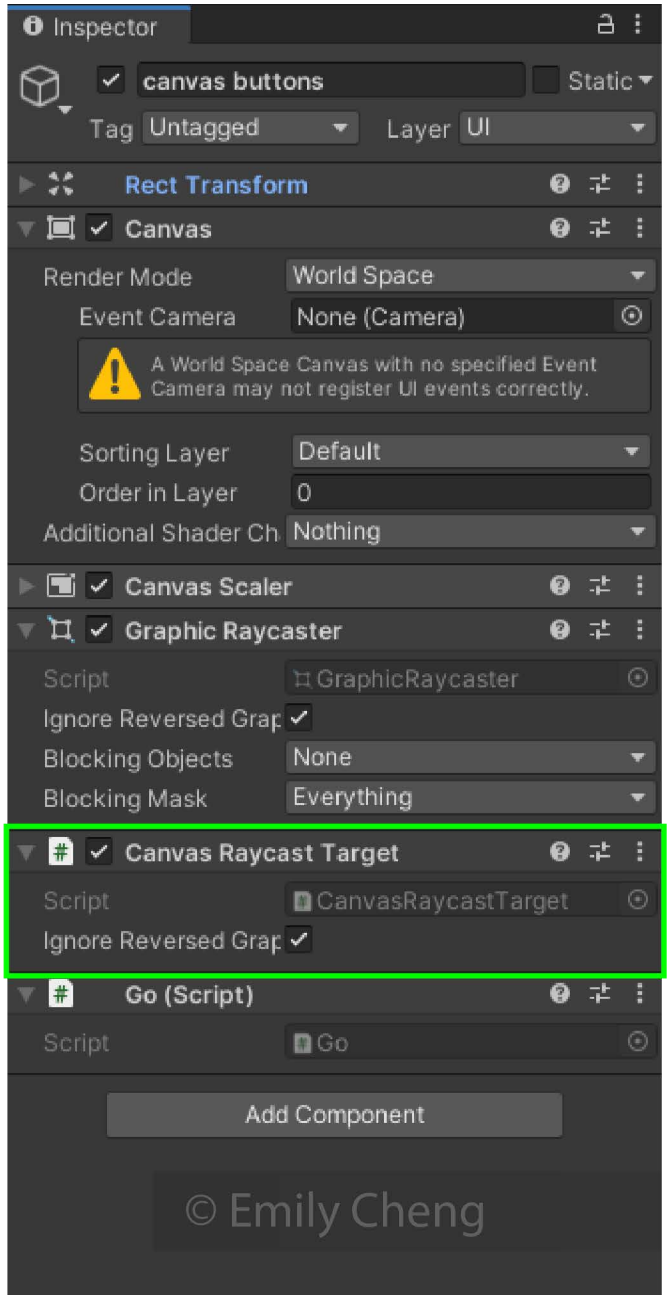


Figure 27. *Example of Canvas Raycast Target Script Added as a Component within a UI Panel.*

Sprite Renderer and 2D sprite

To import the custom user interface assets created through Illustrator as UI elements in Unity, the “2D Sprite” add-on was installed through the Unity Package Manager. Each .PNG file was then dragged in as a new asset, and its

“Texture Type” was changed to “Sprite (2D and UI)” within the inspector panel to register it as a sprite. These sprites were then scriptable within C# through SpriteRenderer API to dictate the situations in which they are rendered. This was applied for functions such as toggling or if certain images pertaining to a selected button were needed.

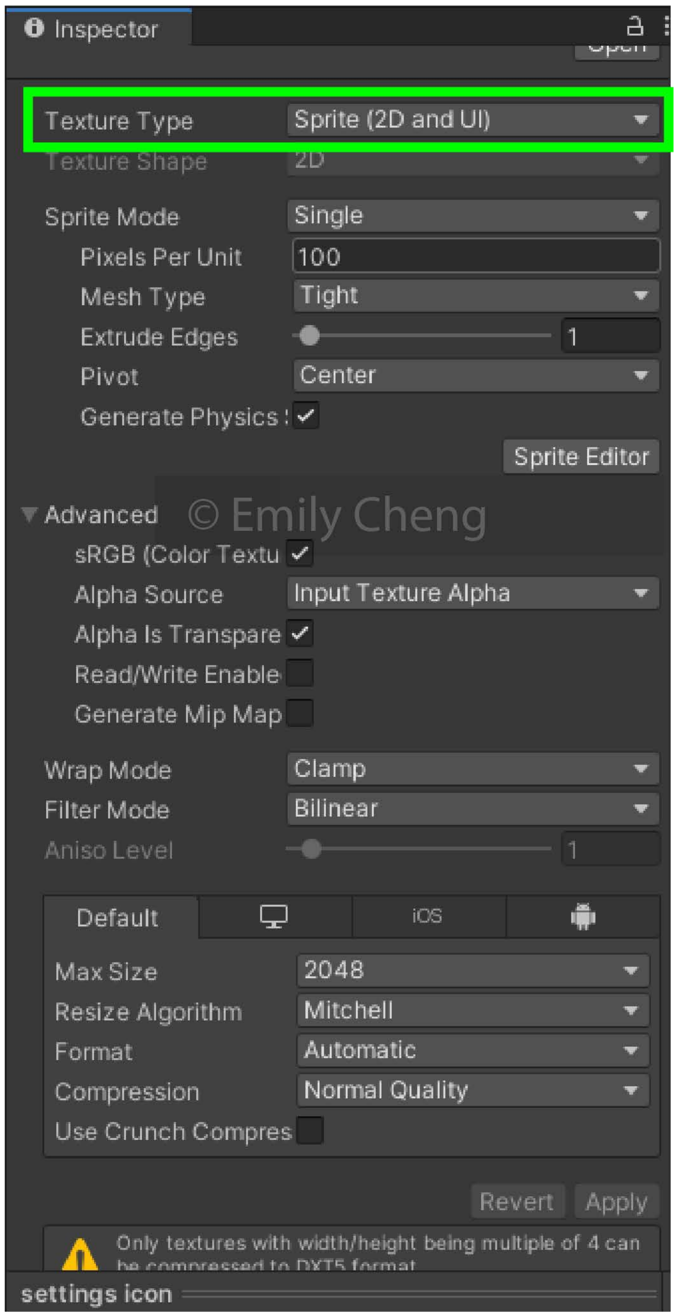


Figure 28. *Inspector with Sprite Registered as 2D and UI.*

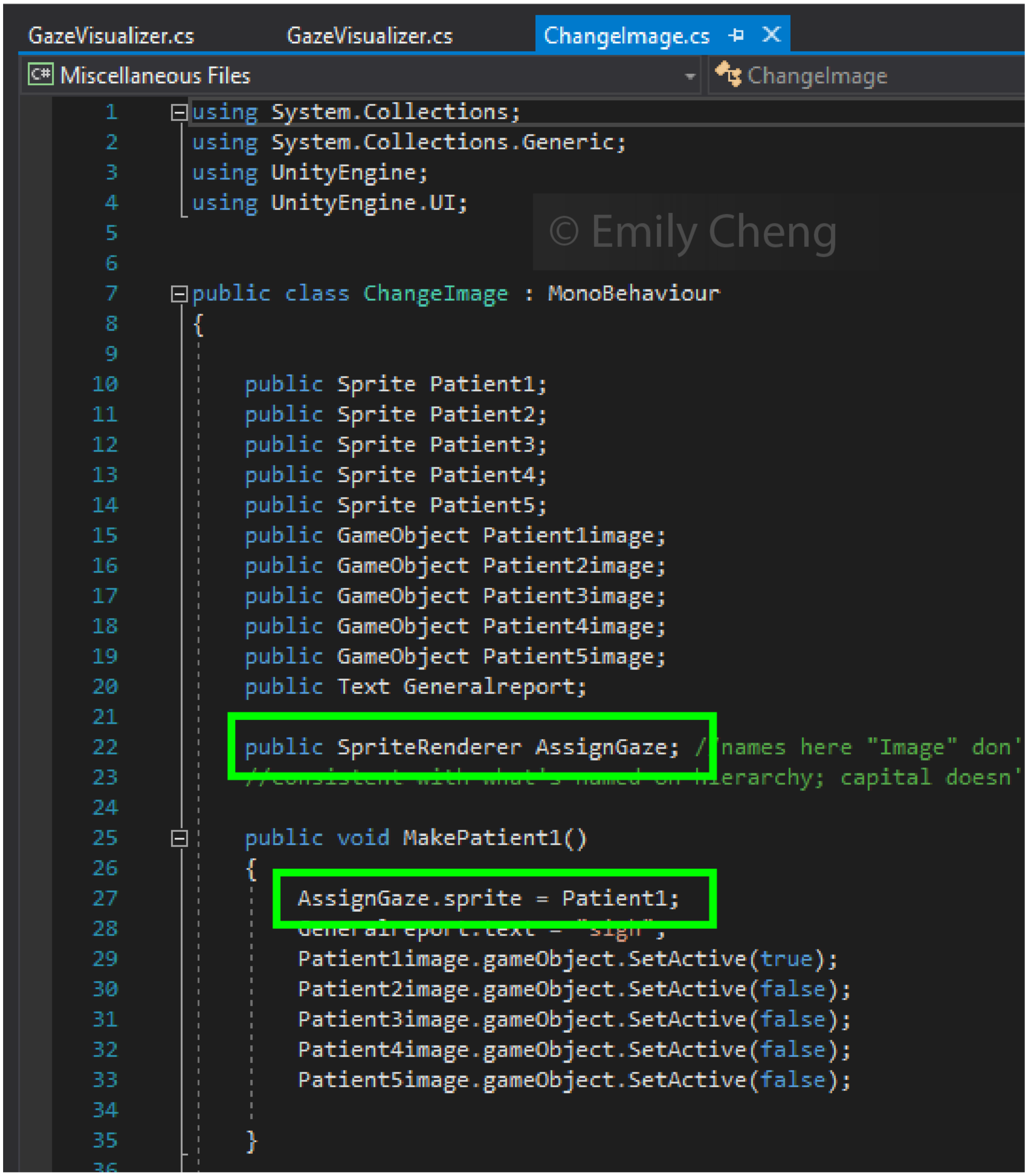


Figure 29. *Screenshot Example of a Script Calling SpriteRenderer for Toggle Effect.*

Activating Eye-Tracking within Unity

Before importing any of the visual assets within the Unity interface, the SRanipal eye-tracking SDK was installed and calibrated for use. The package was installed from the VIVE Enterprise website and is named as

"**VIVE_SRanipalInstaller_1.3.1.1**". Once installed, the SRanipal SDK runs in the background of the desktop. Eye-tracking was then calibrated within the SteamVR lobby settings. Within Unity, SRanipal was imported via Assets > Import Asset Package.

Incorporating Patient Visual Field Masks within VR

In order to incorporate the patient's distortion masks within the VR interface, several asset packages were imported into the Unity through the Assets > Import Asset Package.

The first installed asset package was the Tobii XR Development SDK, which enabled easy access to eye tracking data as well a set of libraries that can expedite cross-platform development. The SDK comprises years of analytics, eye behavior, and foveation technology. The package installed for this research was the "TobiiXRSDK_2.0.0.174". Upon importing into the Unity interface "TobiiXR" prefabs folder becomes available within the project window and **TobiiXR Initializer** can then be dragged into the Scene hierarchy.

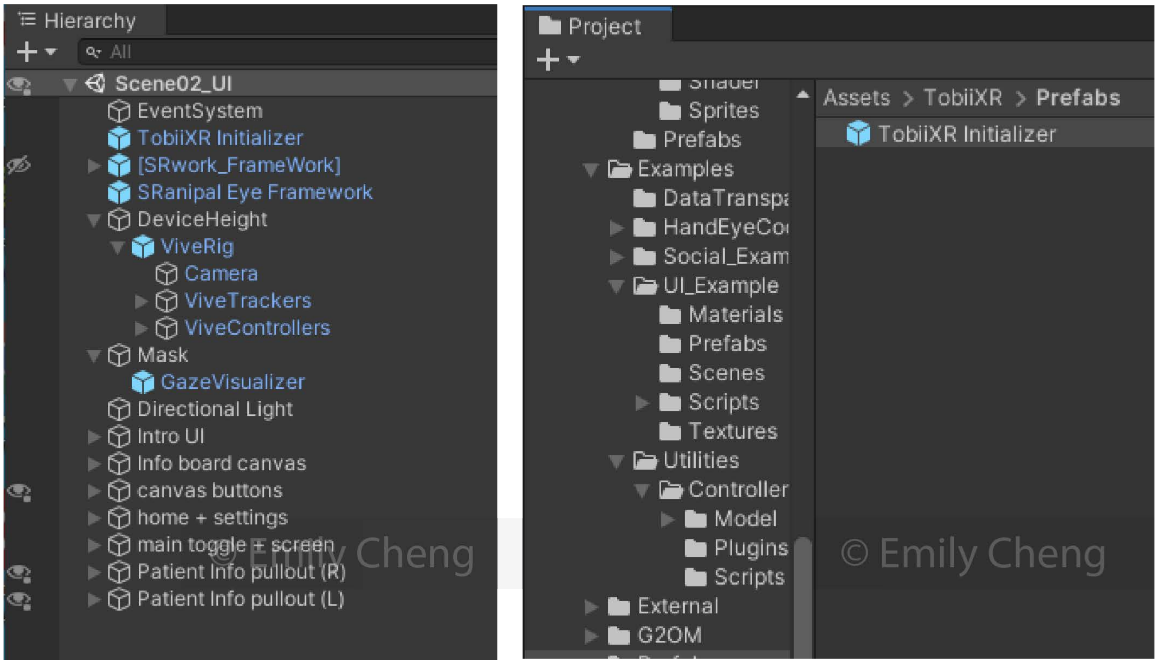


Figure 30. *TobiiXR Initializer Placed within the Hierarchy (Left) and Found within the Project Assets (Right).*

A major tool included within the TobiiXR SDK is the **GazeVisualizer** development tool. The tool was dragged within the Scene hierarchy for us by accessing Asset > TobiiXR > DevTools > Gaze Visualizer (Figure 31). By default, the GazeVisualizer indicates the user's gaze by rendering a circular sprite at the user's gaze point.

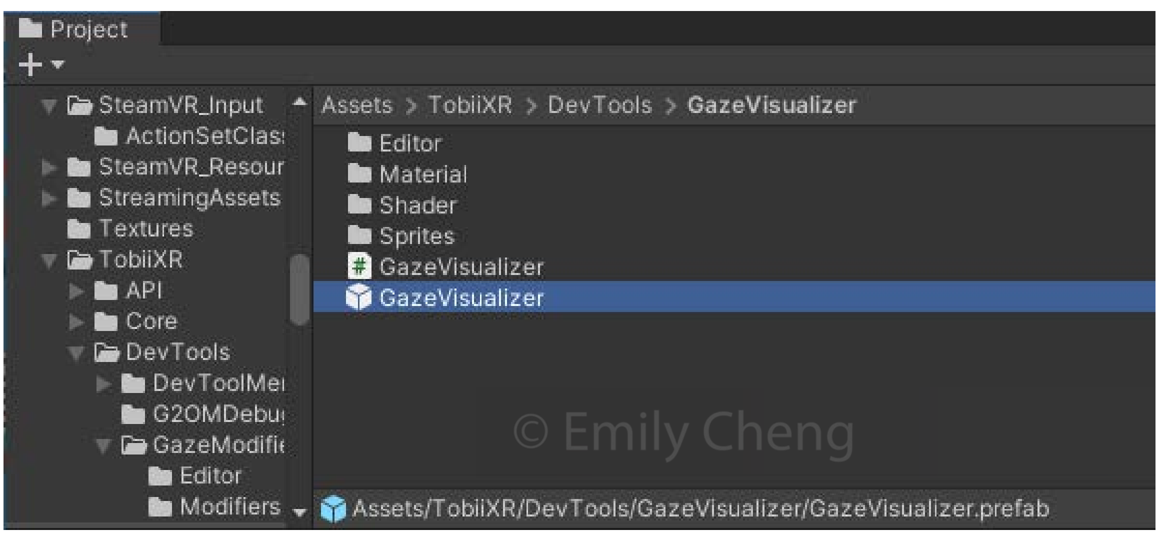


Figure 31. *Gaze Visualizer Found within TobiiXR of the Project Assets.*

The GazeVisualizer was used within this research as the primary method of projecting patient glaucoma masks within the VR space. Within the Inspector panel, the default sprite that the GazeVisualizer uses to indicate the gaze point can be replaced by a different sprite of choice. For this study, the sprites that replace the default are the distortion masks developed through the patient visual assessment interview. These .PNG files were set to "Sprite (2D and UI)" within their "Texture Type" in the inspector panel and then scripted to be brought up by the SpriteRenderer when called within the user interface (Figure 32).

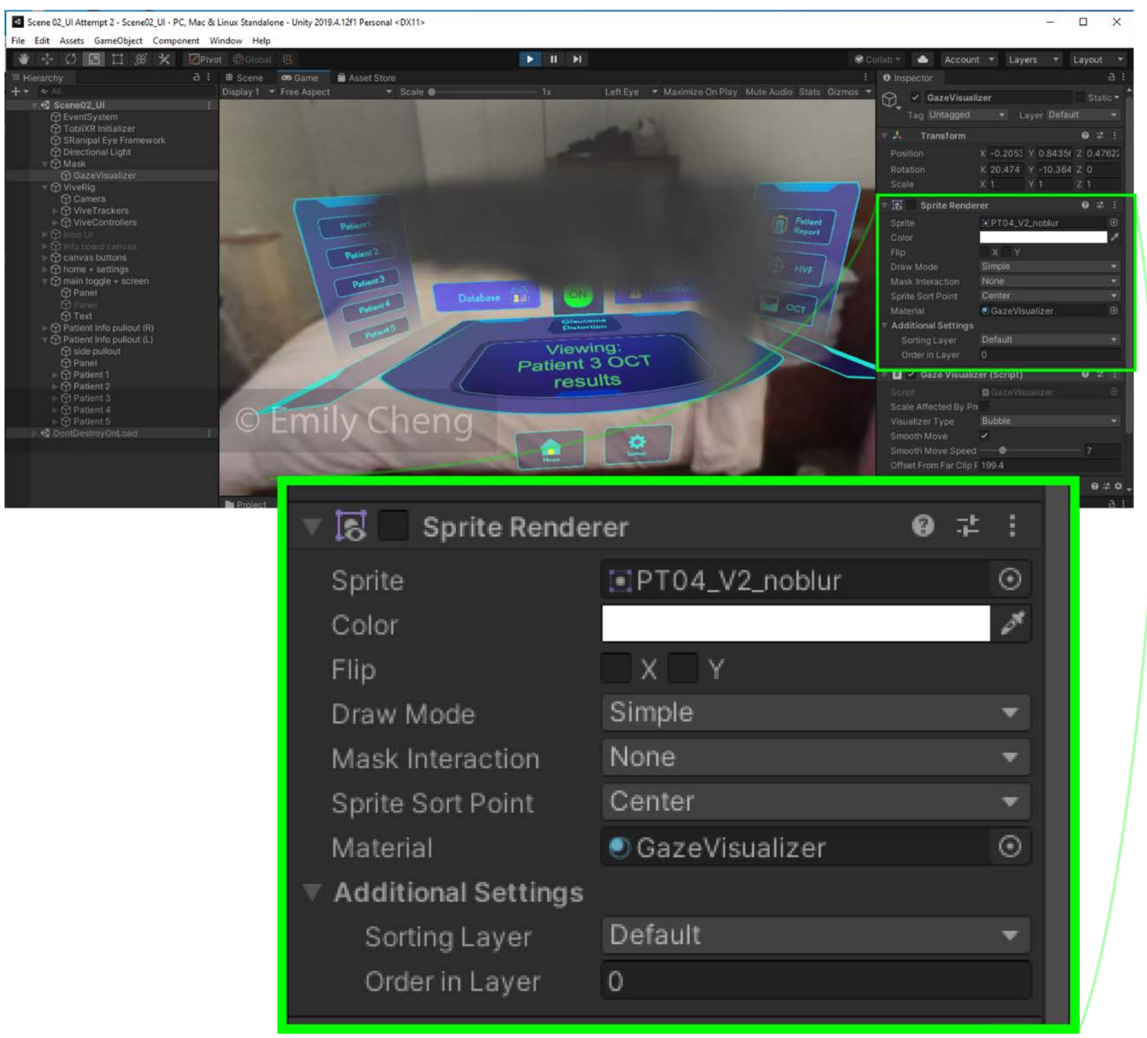


Figure 32. *Script of GazeVisualizer using Sprite Renderer to call up 2D Mask. Not all text intended to be read.*

Once applied within Unity3D, the size and distance of the mask was adjusted to reflect the arrangement patients had at their first interview in clinic. To do this, we first referenced default Unity measurements, which equates one (1) Unity unit to 1 meter. The objective was to resize the imported sprite and place it at the proper distance away from the camera relative to this scale.

To address the distance with which the sprite is placed, GazeVisualizer script was directly modified (Figure 33). The full script is available in Appendix E. First, the variable controlling sprite distance known as the "OffsetFromFarClipPlane" was made public so it becomes accessible within the Unity interface. The far camera clipping plane from our VRrig, or the maximum distance with which an image on the camera is rendered, was set to 200. The 60cm distance patients sat from the screen used for visual assessment was scaled in proportion to Unity units and calculated to be **0.6 of a Unity unit.** Therefore, to project the sprite at this distance, the following equation is used:

Input variable = "OffsetFromFarClipPlane"– desired distance projected

Input variable = 200 – 0.6 = 199.4

199.4 was therefore inputted to achieve the 60cm (0.6 units) arrangement we had during patient interviews within the VR setting. Another line of code was also modified in order to preserve the aspect of the image being rendered by Gaze Visualizer.

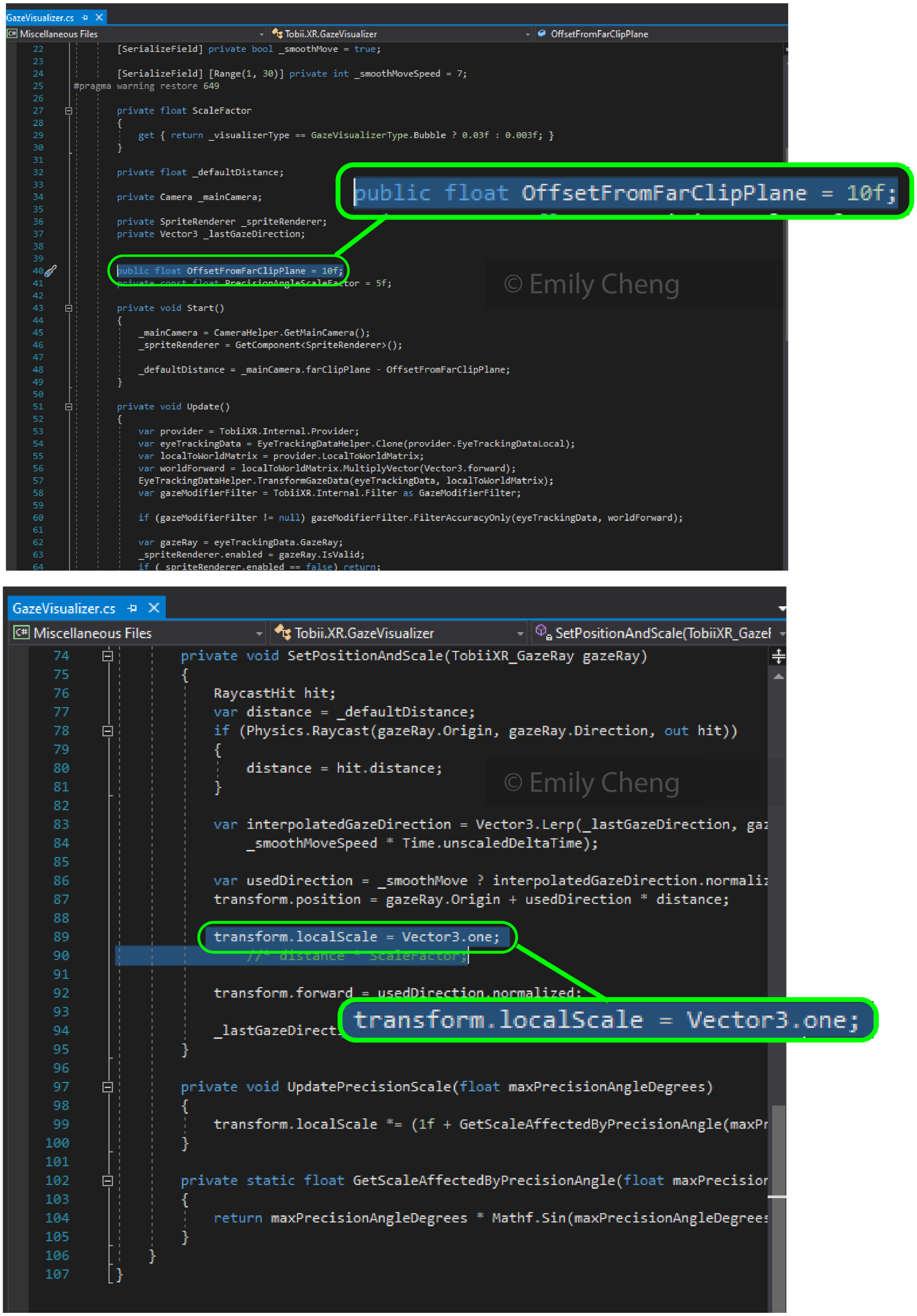


Figure 33. *GazeVisualizer Script Modifications. Not all text intended to be read.*

The image also needed to be imported at the size it was projected on the LG monitor. Within Unity, the image scale is manipulated by calculating the pixels per unit (PPU) that the imported .PNG sprite is rendered at. To do this, the following measurements were taken:

- The length of the grid within the document: **8.75 in**
- The length of the grid when projected on the 38" monitor (desired scale): **30.58 in**

The following measurements were calculated:

- The pixels of the grid in document: x = 5760px (document total px) * 8.75 in (grid length)/ 19.2 in (document length) = **2625 px per 30.58 in**
- **The total pixels per meter (unit) = PPU** needed to be entered for image to be projected at desired scale = x = 2625px*39.37in (1m)/30.58 in = **3380 PPU**

This number was then inputted into the inspector panel of the uploaded sprite so that it takes on the proper size in the VR setting. The sprites were also set to 8049 px with no compression as the setting to ensure they retain their original size.

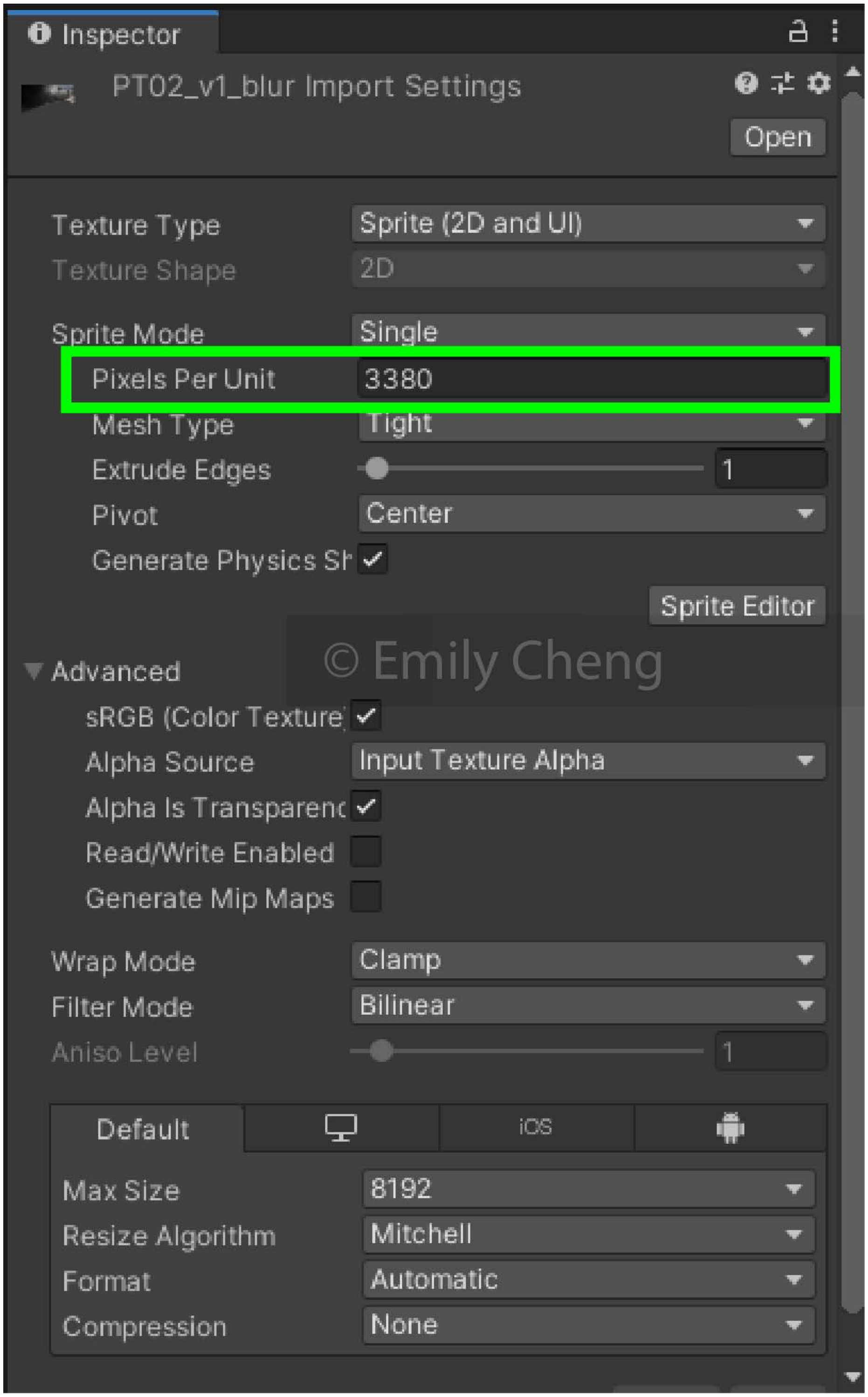


Figure 34. *Inspector Window of Patient Mask with Inputted Calculated Sprite PPU.*

Building the Main Scene Using Blender and Unity

The user is first greeted by the main scene when launching the VR application. Several assets contribute to its overall appearance. The first subtle asset is the environment, which was developed by creating a custom "Skybox" within Unity. Custom Skyboxes can be imported as 6-sided images that form a cube that Unity uses to simulate a surrounding environment.

To produce this, the storyboard concept, previously designed along with the user interface, was first referenced and refined (Figure 24). The concept for the environment consists of positioning the user within the posterior chamber of the eye. The view was oriented to the posterior aspect of posterior chamber (seeing the optic disc and retinal vessels) and behind the user is the anterior aspect of the posterior chamber. The asset for the retina (depicted up to the ora serrata) was then traditionally sketched, scanned and digitally illustrated using Photoshop (Figure 35).

The resulting image was then UV mapped onto hemispheres within Blender and lighting was arranged to achieve the desired render. To obtain the six images needed to construct a six-sided cube for Unity's custom skybox, six 2048x2048 cameras were oriented side by side and a rendered image was captured from each camera view (Figure 36). The final six images were imported into Unity as 2D sprites and then dragged into the skybox inspector which was then set as the new skybox within the main page scene.

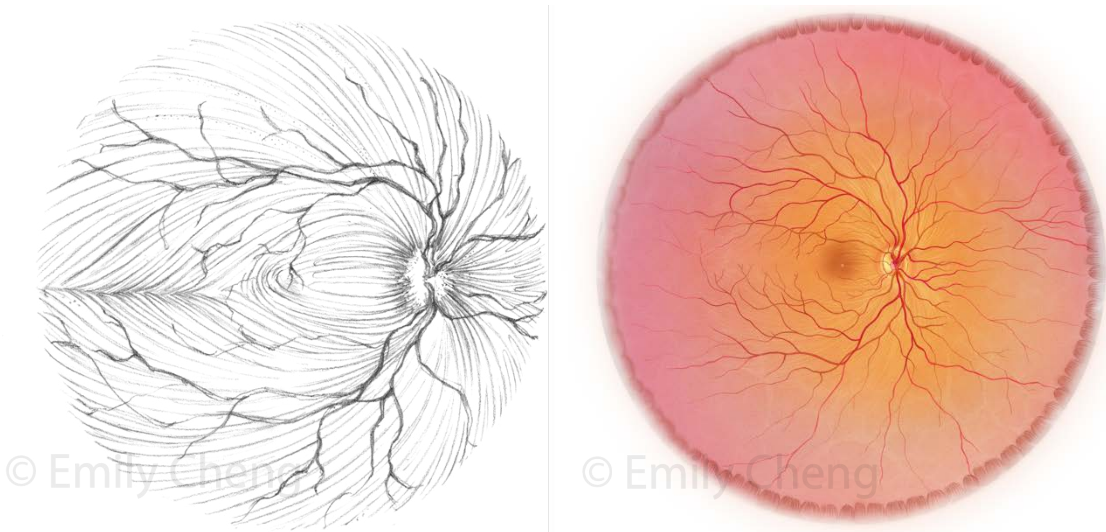


Figure 35. *Sketch of the Fundus of the Retina (Left) and Final Digital Render (Right).*

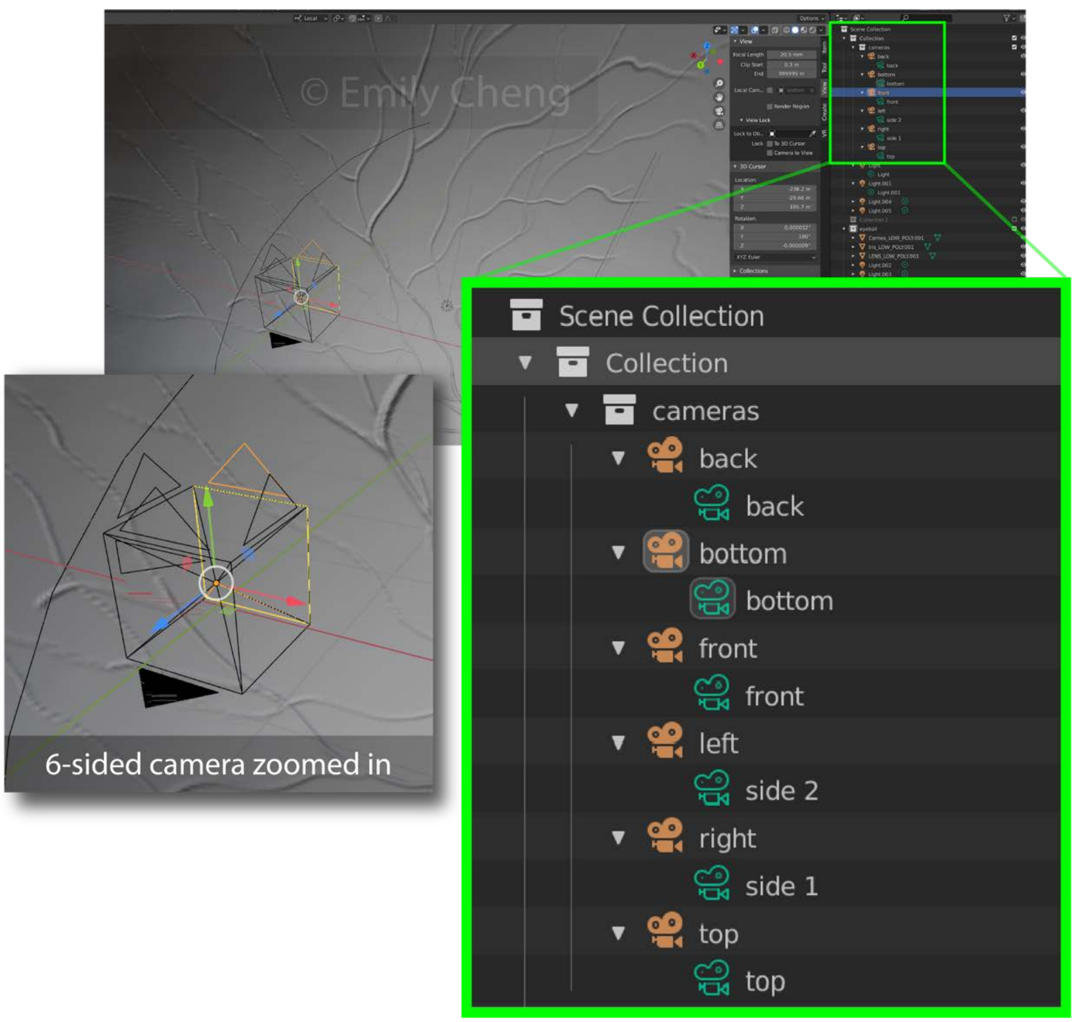


Figure 36. *Six Camera View in Blender with Hierarchy (Highlighted). Expanded boxes meant to be read.*

Figure 37. *Preview Cycles Render of Front Facing Camera within Six-Camera Set-up in Blender.*

An important feature of the main scene is allowing the user to interact with spherical “orbs” to access different modules. Each orb is an interactable object, which once selected, allows the user to enter into the selected module. The forcefield-like aesthetic of the orb was created through Unity Physically Based Render (PBR) Shaders and the animation was an added property within the Unity Interface. A PBR shader was generated within the Project window through Create > Shader > PBR shader and corresponding properties were edited within the Inspector (Figure 38).

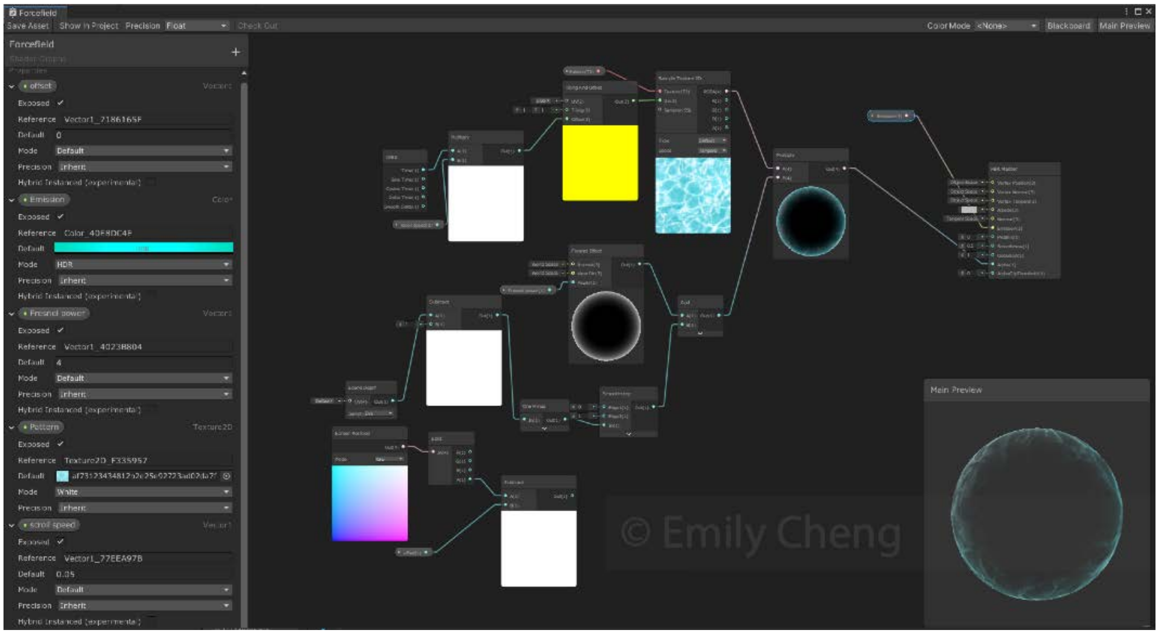


Figure 38. *Screenshot of PBR Forcefield Shaders. Text not intended to be read.*

Development of the Live-Camera Module within VR using Unity

Utilizing the live, front-facing camera on the HTC VIVE Pro-Eye headset requires importing two separate Unity plug-in and packages called SRWorks (XR) Unity Pre-built Samples (Plugin and Demo) and SRWorks Runtime. SRWorks Runtime contains a Depth module, a See-through module, an AI module, and a 3D reconstruction module that is supported for development within Unity. This was installed through Unity > Assets> Import Package > Custom Package.

To test for successful functionality of SRWorks, SteamVR was accessed and the following sequence was initiated, Menu > Settings > Camera > Start Test. SRWorks runtime was then opened within Unity via Assets > ViveSR > Prefabs and the [SRwork_Framework] prefab was dragged into the scene in order to activate the HTC VIVE front facing camera. Once the front-facing camera was activated, the user interface GameObjects were constructed within the hierarchy and scripted to appear when desired.

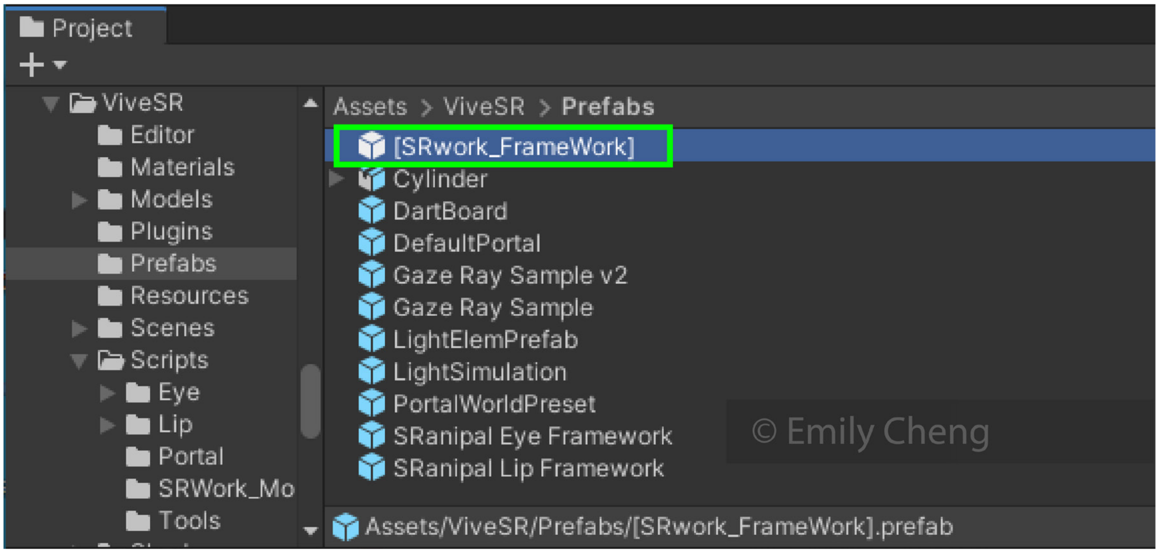


Figure 39. *SRWorks Screenshot Highlighted in Green.*

Development of Search Task Simulation Module and VR 3D Modeled Environment using Unity, and Blender

For the Search Task simulation module, a 3D-modeled environment was built using Blender, textured and materialized within Blender and Unity, and incorporated within the VR environment using Unity. A breakdown of the steps used follows:

Reference Material

Photos of a living room were used as initial reference material to obtain the aesthetic feel of the desired environment. The objective was to portray a “lived-in” family home that contained some “visual clutter”.

Figure 40. *Living room Reference Images.*

Building the Living Room 3D Models

Blender was used to build the simulated 3D living room for the Search Task module. Various 3D models were created referencing the photos of the living room in order to build the various assets present in the environment. This included couches, fireplace, dining table, coffee tables, chairs, books, CDs, lights, pages, picture frames, plants, and paper. Two particularly important assets that were modeled within this scene were a television set and remote control. These two models are play a primary role in the search task objective.

Furniture	**Accessories**
3 seated couch	Books (x?)
Single seated couch	CDs
Coffee table	Paper (stacks, sheets, envelopes)
Side table	Laptop
Dining table	Calculator
Dining chairs x 4	Coasters
Bookshelf	Cups, mugs, drinking glasses
Door	Picture frames
Fireplace	Pens
Interior walls	

Table 3. *Different Interior Design Assets Built within Blender*

All of the assets were created using similar Blender commands. Commonly used commands included the **extrude** function, which creates an impression based on the direction of movement within a shape. This was effective for creating edges for frames, as well as the screen for the television. Multiple **loop cuts** were also used to create new polygon faces that make the geometry easier to manipulate or control in desired areas. This was useful for generating curvature within objects without creating too many polygons. **Beveling** softens many of the object edges to offer a more realistic portrayal without tremendously hiking up the geometry. Examples of these commands are shown in Figure 41.

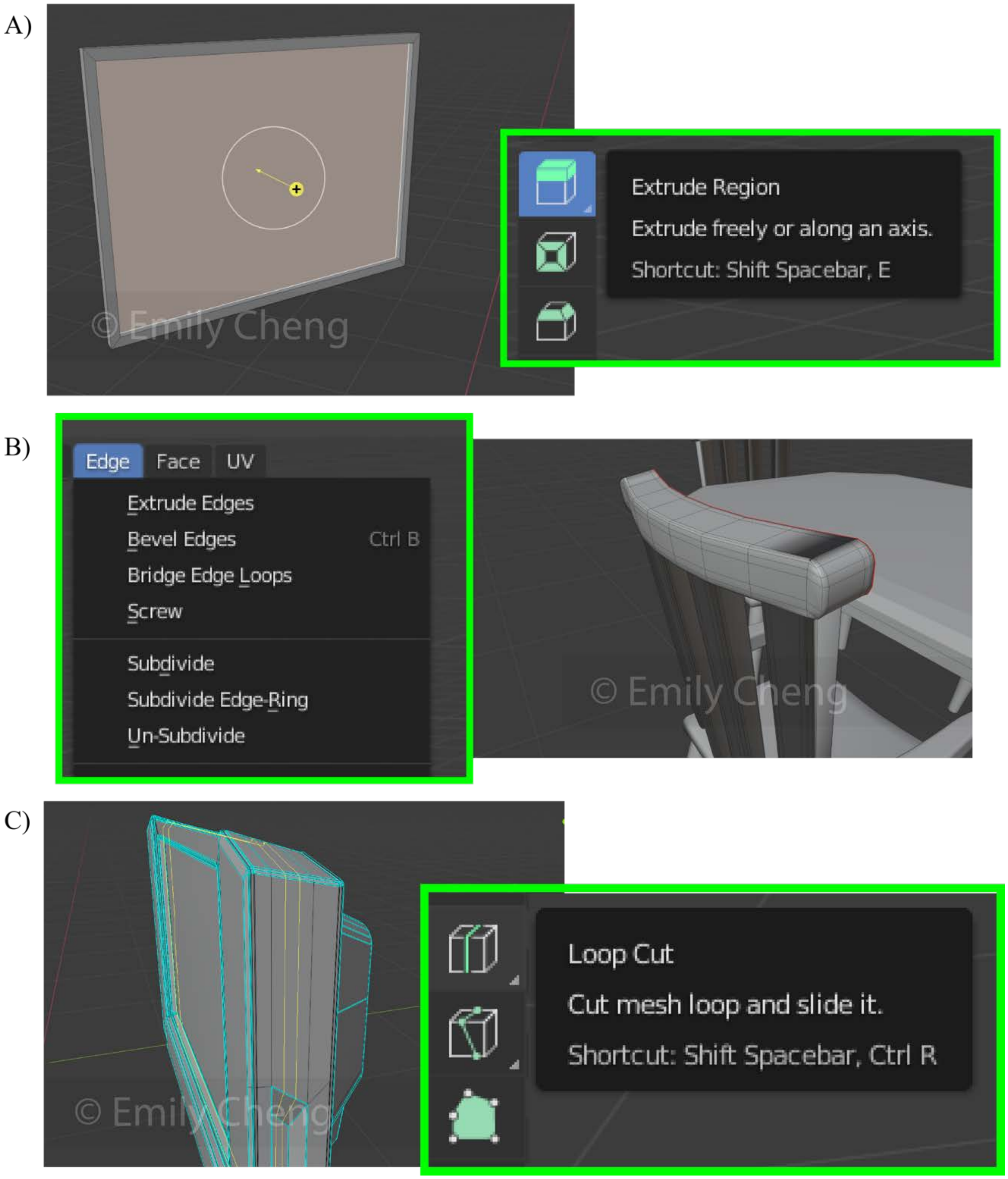


Figure 41. *Different Blender Tools and Examples (A) Extruding performed for to create frames (B) Beveling on edges of dining chairs (C) Loop cuts to generate geometry on TV.*

Maintaining a Low Polygon Count Environment

The simulation room was kept below 150k triangles in order to ensure that it could be rendered smoothly without affecting performance within the VR headset. Objects modeled within the scene were therefore designed to achieve a low polygon count. Certain techniques were implemented to help achieve this. Blender comes with a "**Shade Smooth**" feature, which displays the best smooth surface rendering regardless of the polygon count. Unity incorporates the shade smooth function, and therefore allows minimal use of polygons to achieve a deceptively higher polygon appearance. A decisive effort to reduce subdivision levels and modeling of intricate curvatures was also made to maintain low polygon count geometry.

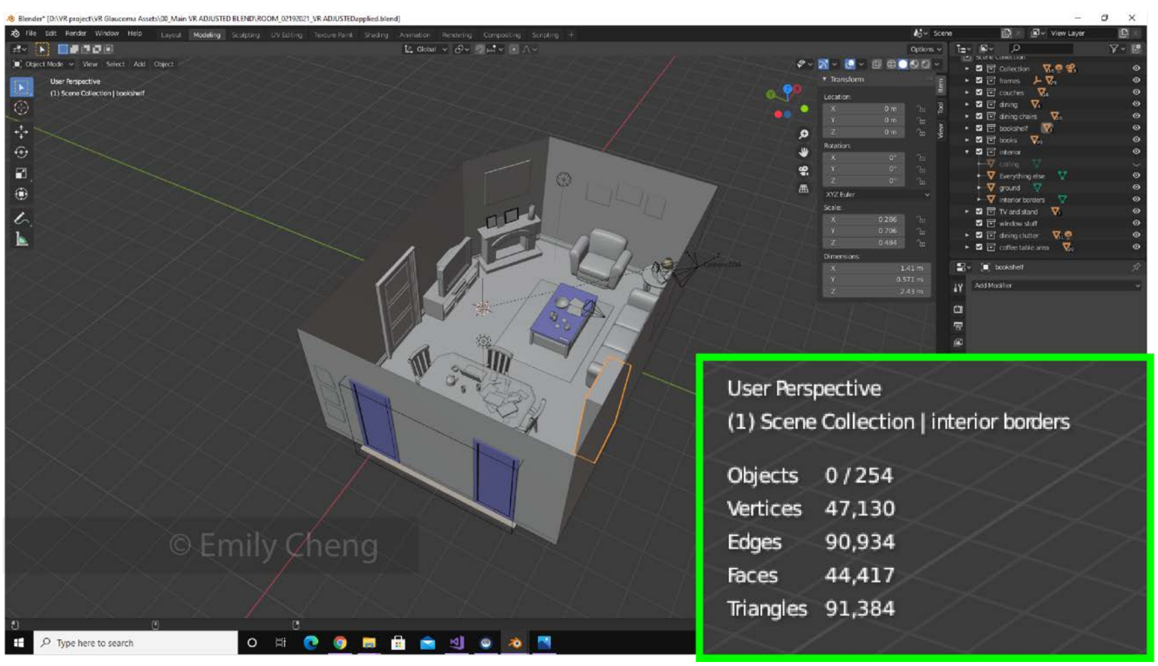


Figure 42. *Screenshot of Polygon Count of Full Model.*
Only highlighted text meant to be read.

Scaling Size and Proportions of Assets Using Blender

In order to ensure the assets created within Blender ae at a believable and realistic scale in VR, the asset proportions needed to be adjusted. As an overall adjustment, models were first resized to an average measurement relative to a 1.7m (5′7″) human height. The updated model dimensions were shown within the Transform panel in the Modeling editor (Figure 43).

For more subtle adjustments, Blender 2.9.1 comes with a VR viewing interface as one of its numerous add-ons. With the VR add-on activated, the scene can be adjusted directly within Blender while verified through the VIVE headset (Figure 44).

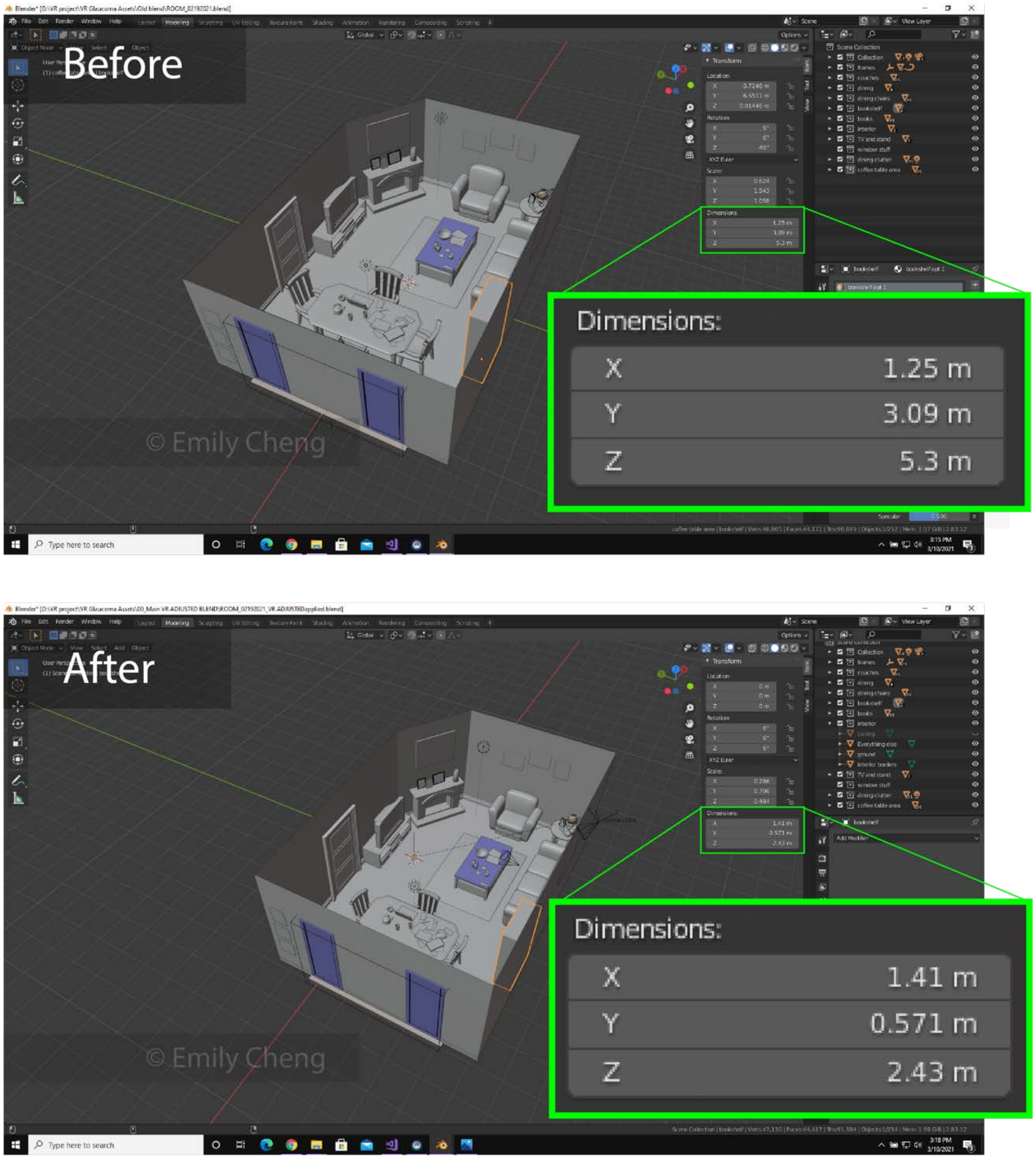


Figure 43. *Image of Simulated Room Before (Above) Adjustments vs. After (Below) Adjustments. Dimensions of book of orange highlighted bookcase compared. Only highlighted text meant to be read.*

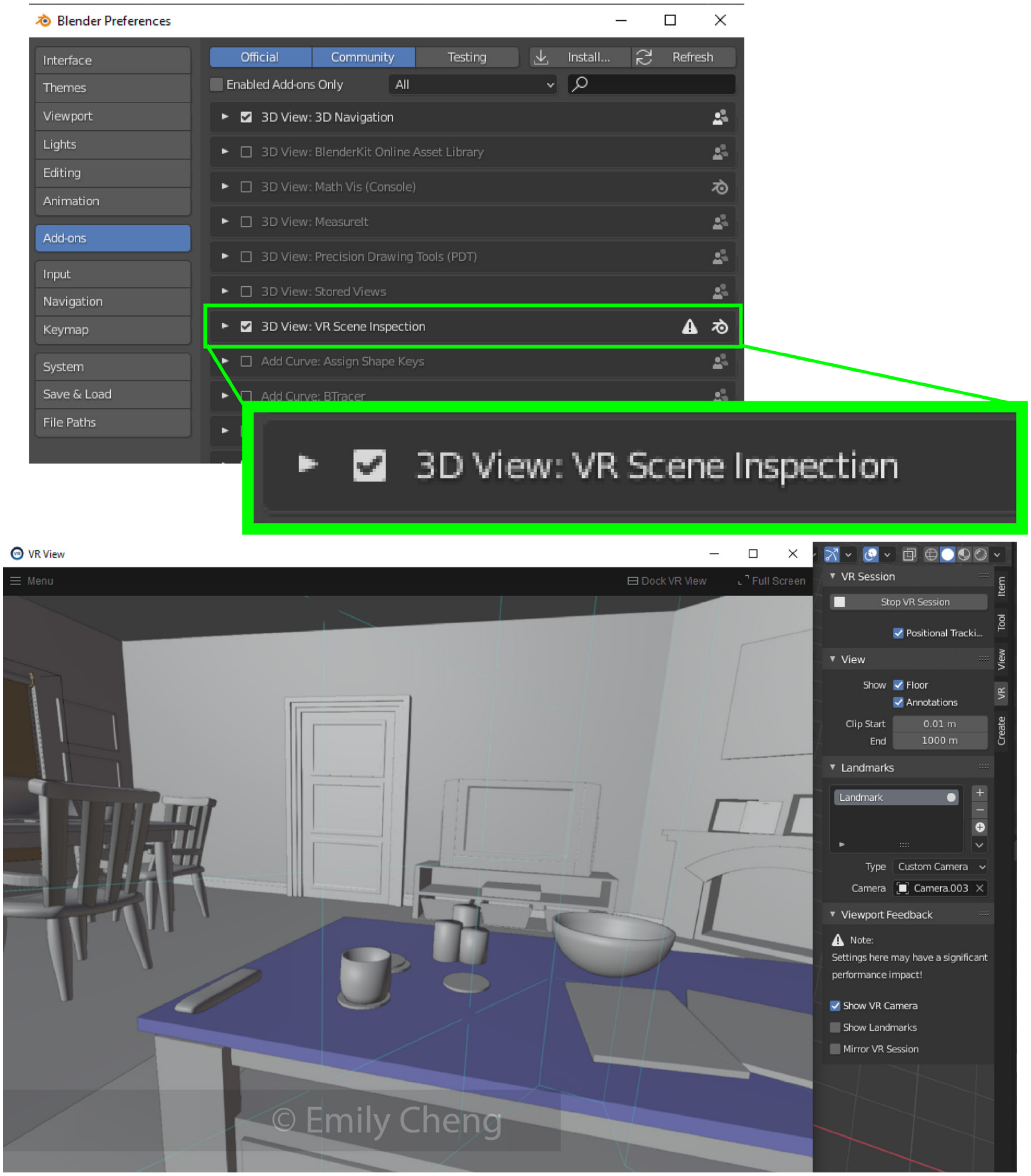


Figure 44. *VR Scene Inspection Add-On with orresponding VR View of Living Room Assets. Not all text intended to be read.*

Textures: Applying Normal, Displacement, AO, and UV Maps

Textures were sourced from personal artwork, photographs, and royalty free image searches in addition to a library of PBR textures from Cgbookcase, Cc0textures, and Sharetextures. The texture packages included normal, displacement, ambient occlusion, and roughness maps that can be applied to the models within Blender's Shading editor.

The pattern on these textures were first UV mapped onto desired 3D object. The object was then unwrapped in "Edit Mode" under the "UV Unwrap" tab in the menu bar. By pressing "U" while in Edit mode, and then "Unwrap," the polygons were automatically projected onto a flattened version of the object. The texture image of interest was then pulled up underneath the polygons, and the position of polygon vertices were manipulated to incorporate the desired texture onto the object.

In order to have the texture properly projected onto the object in render mode, a material with the texture as its color must be created and placed on the object. This was done in the "Shading" Editor window in the menu bar. This editor allows the user to drag the texture, the albedo (or diffuse color map), the normal maps, roughness, and ambient occlusion maps to build into Principal BSDF material shader. To obtain the color texture, the Albedo map was placed and its "Color" output was connected into the "Base Color" input of the Principal BSDF.

Textures for objects that were not meant to be observed in spotlight were combined into one large texture map in and applied to each varying object as a single material. Examples include pictures within frames, books within the bookshelf, and papers on the dining table. This is useful for conserving polygon count use and maintaining overall performance within the scene.

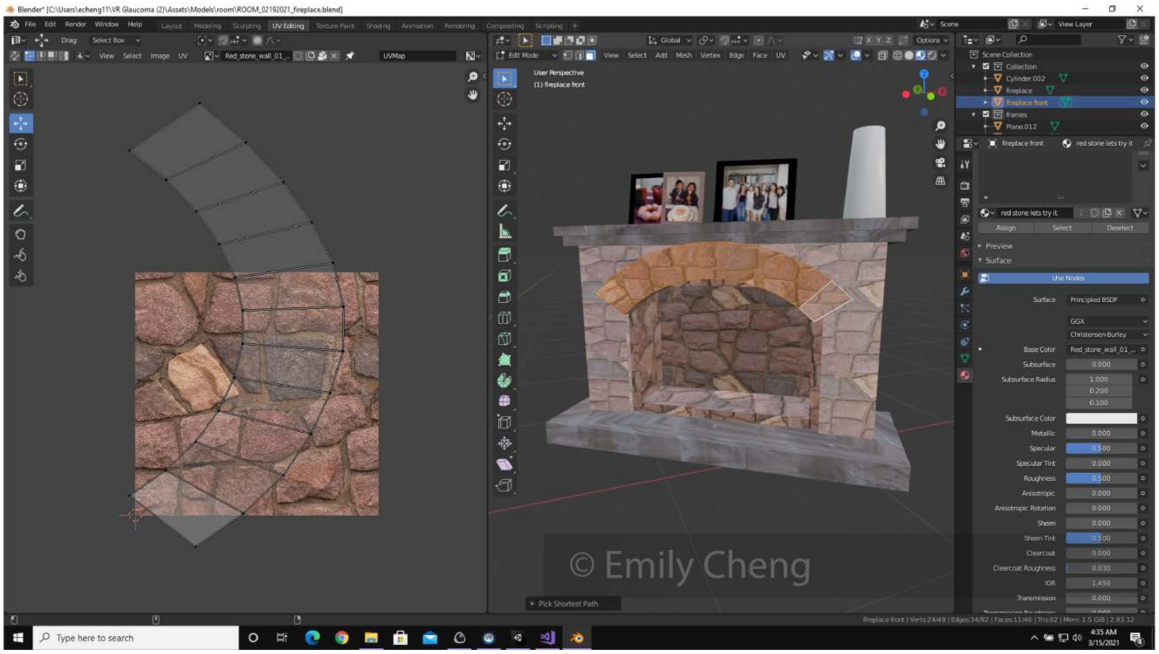


Figure 45. *Screenshot of UV Mapping Workflow in Blender. Text not meant to be read.*

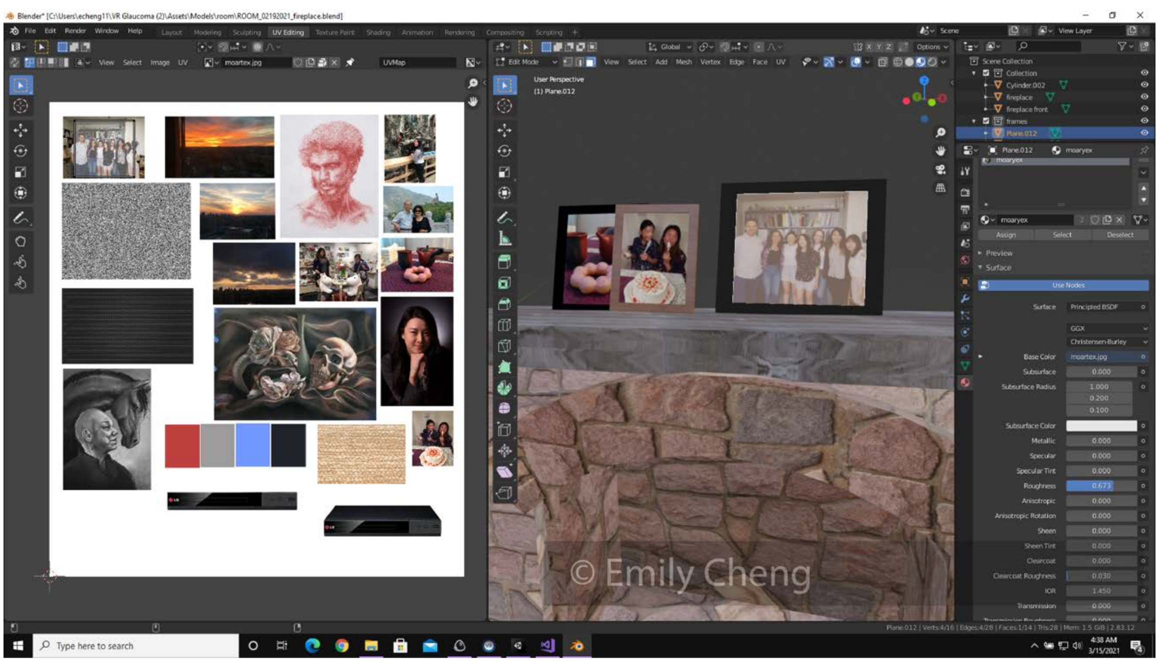


Figure 46. *Sample Image of Multiple Free Textures Combined into One JPEG Image to Import into Blender for UV Mapping. Text not intended to be read.*

Exporting FBX with Normal, Displacement, AO Maps to Import into Unity

All objects in the scene were then separated into different Blender .blend files to drag directly into Unity. Within each blend file, the option for packing all textures into the file was checked. This allows for all of texture maps to be imported directly into the Unity interface when Unity converts the models to FBX files.

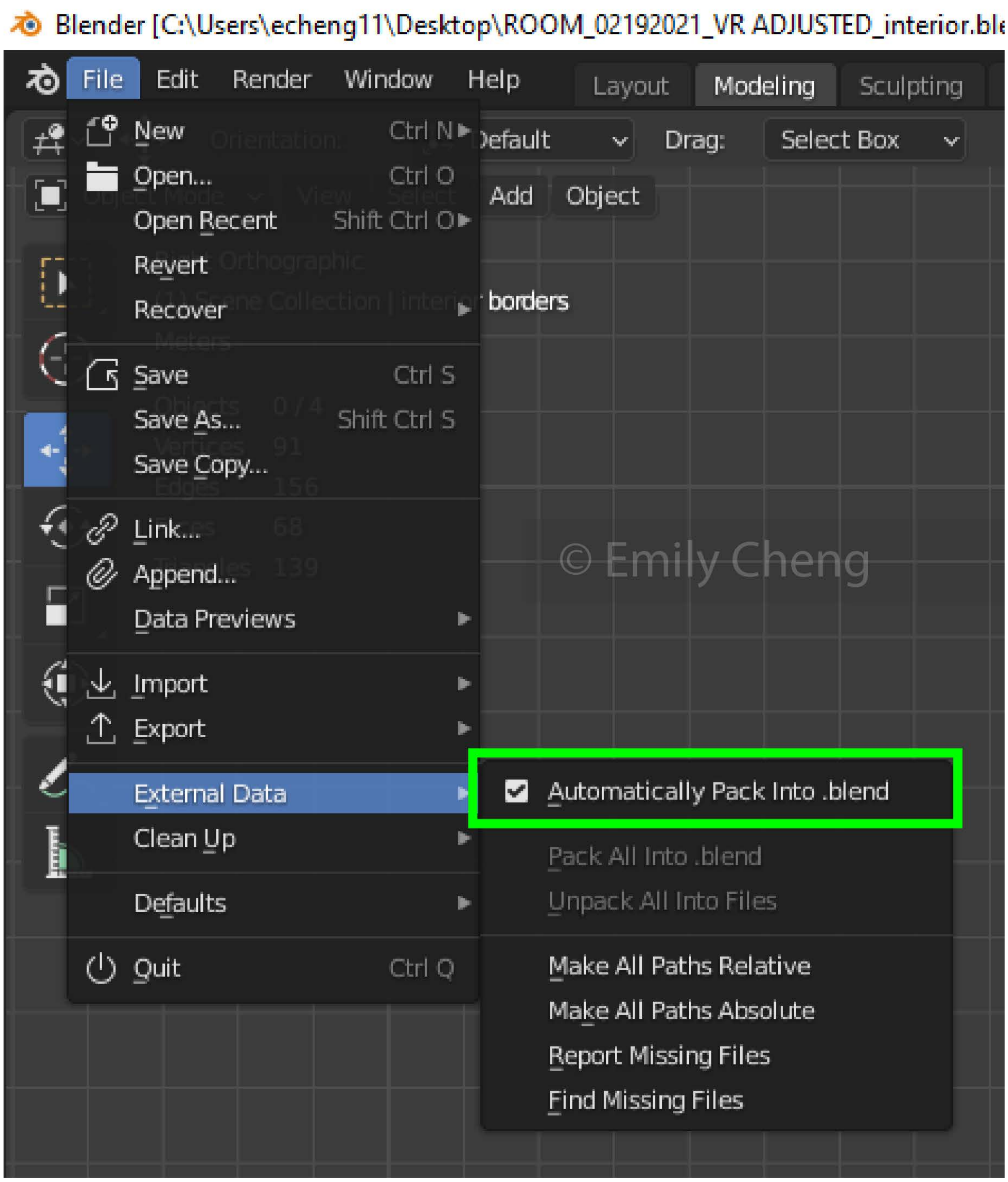


Figure 47. *Screenshot of Window for Packing Textures into .blend File to Prepare for Import into Unity3D.*

Incorporating Interaction with Living Room Objects within Unity3D

The primary levels of interaction within the Search Task Simulator module includes physical interaction between the user and the remote control and searching for that object successfully within a certain time frame. With the exception of the remote control, all of the interior room assets are meant to be surrounding objects and were therefore set to be **"Static"** within the Inspector.

A custom C# script was written to achieve interactivity between the user and remote control. The script contains commands that control the timer upon interaction with the remote when the user grabs the object. This script was added as a component to the remote control object. Part of the script involves placing an input code that assigns the VIVE hand controller buttons in order to trigger the grab. This can be customized by adjusting the binding user interface through Windows > SteamVR Input > Open Binding UI.

Two additional scripts were added into the remote control Inspector to allow it to function as a grabbable object. The "BasicGrabbable" script allows the interface to recognize the remote as a grabbable object. The "StickyGrabbable" allows the remote to remain attached to the user's controller after interaction. Both scripts work in conjunction with the custom script in order to stop the timer and provide feedback of a successful player interaction

Creating Patient Education 3D Models, Rigging, and Animation

Multiple 3D models were created for cross-platform use in both educational animations and the VR application. The models include: (i) an eyeball with iris, lens and cornea structures, (ii) an eyeball cross-sectioned just medial to the optic disk to maintain view of the optic nerve while revealing anterior structures, and (iii) an eyeball posteriorly cross-sectioned to showcase the optic nerve (Figure 48).

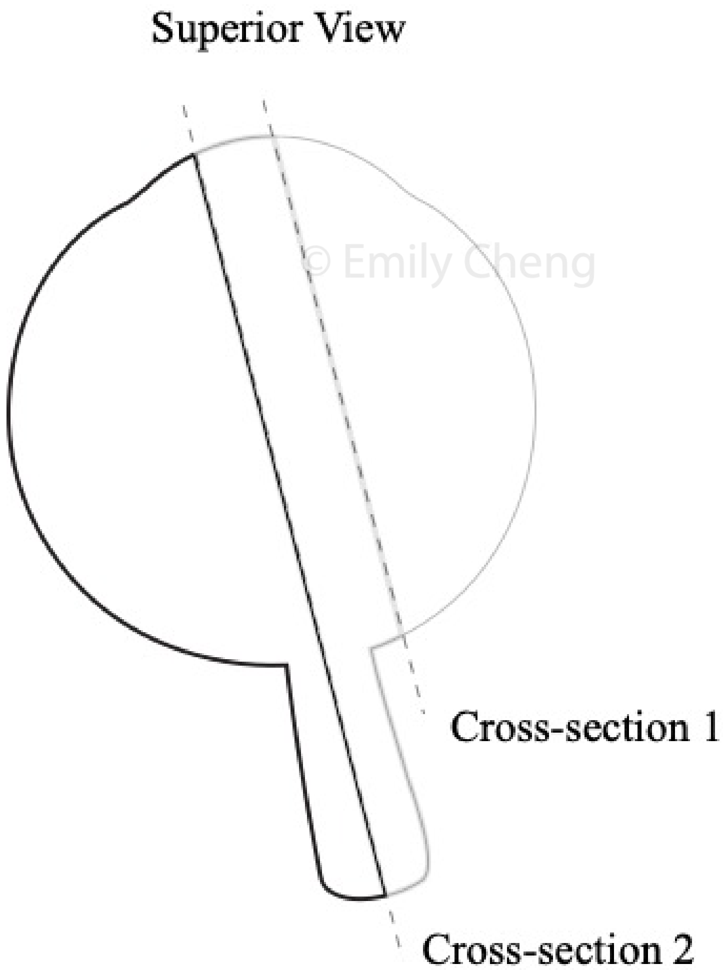


Figure 48. *Cross-sections Taken within the 3D Model.*

Making the Eye Model

To create the 3D eye model, a cross-sectional line drawing of an eye created using Illustrator (Figure 133 in Appendix G) was imported into **Cinema4D** as **splines**. The splines were then lathed using the **lathe tool**. This generated most of the internal anatomical structures while also forming the rough 3D shape of an eye (Figure 49).

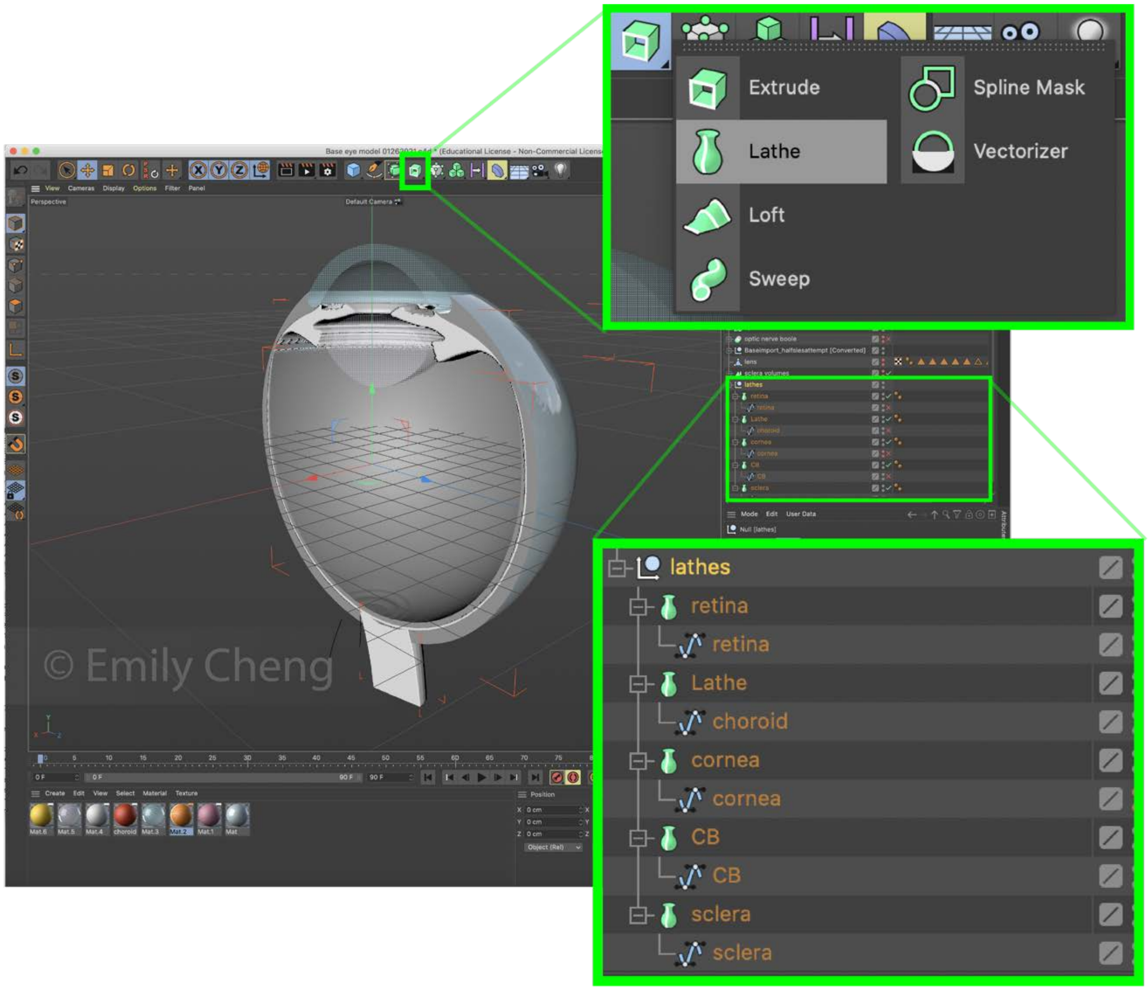


Figure 49. Lathed Splines in C4D. Booleans were shown to reveal detail of lathed structures underneath.

This preliminary model was then imported into **ZBrush** where **Boolean** and **ZRemesh** operations were performed. Two cube primitive subtools were appended to generate two separate desired cross-sectional views via a boolean subtract operation. Position of these two appended primitives were adjusted to retain structures pertinent to the educational objectives. The first such cross-section allowed visualization of the Canal of Schlemm and corneo-scleral angle, and was positioned to also show the anterior chamber of the eye while preserving the entire optic disc. This view facilitated an animation used to discuss how light is processed by the eye. The second generated cross-section was through the optic disc, allowing for an animation that explains how the action potential signal is passed from retinal nerve fibers to the optic nerve. All the models thus generated were then further sculpted upon, remeshed using ZRemesher, and prepared for subsequent finishing steps. Materials were applied using the **Color> Fill Object** menu (with mRGB model on) and subsequently colorized using **Polypaint** mode in order to achieve the desired effect. To depict the retinal vessels accurately, an illustration was mapped into the internal posterior aspect of the model using **Spotlight texturing.** A .PNG illustration of the retina made using Photoshop was imported using Texture>Import (Figure 50). The retina spotlight texture image was positioned over the correct part of the 3D model, the model was **Dynameshed** to achieve greater mesh resolution, and finally the texture was painted onto the 3D model as Polypaint (with RGB mode and Spotlight projection options turned on).

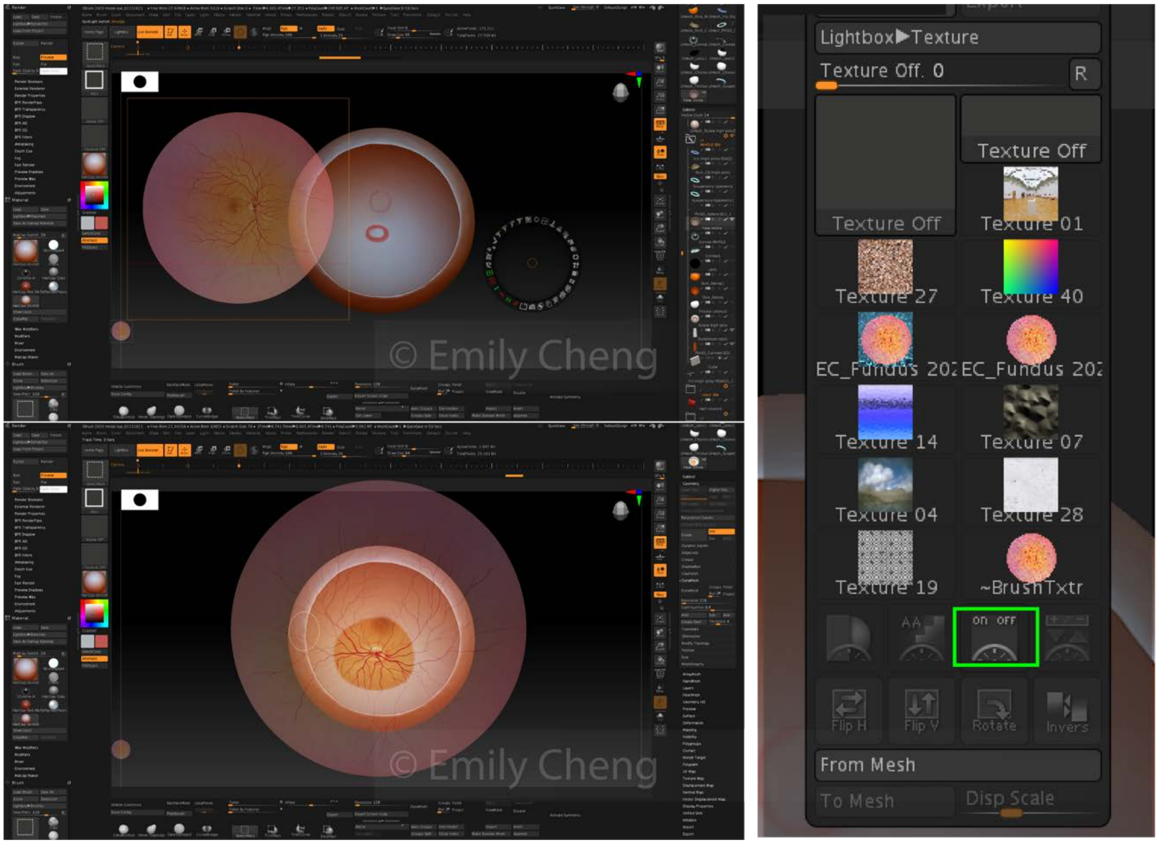


Figure 50. *Screenshot of Spotlight Texturing (Left) and Corresponding Texture and Spotlight Tool Menu (Right). Text not intended to be read.*

Creating the Patient Education Animation

To develop the patient education animation, a rough draft of a script and storyboard were created to identify the most effective teaching views for the 3D models as well as the important educational concepts to illustrate. All narration elements were also scripted. Given time constraints it was decided to proceed with the introductory portion as a sample for future development. The Introductory storyboard was thus further refined for animation.

The 3D assets used within the introductory portion include all 3 developed eye models (whole eye and 2 cross-sections) made using ZBrush. Using the ZBrush **Timeline** (Movie > ShowTimeline) feature, different positions of the whole eye, cross-sectioned eye, and the cross-sectioned optic nerve were keyframed. A Best Preview Render (**BPR**) pass was conducted on the starting frame before Ctrl+Shift+clicking on the Time Cursor to render out the remainder of the animation frames with BPR. The animations were then recorded separately at 24fps and exported as QuickTime movies through the Movie > **Export** button to be further post-processed.

To better introduce some anatomical concepts within the introductory animation, an inset image was made using Photoshop. This image shows the various cell layers of the retina with a focus on the retinal ganglion cells. The inset was saved as a .PSD file to be incorporated into the final animation.

Adobe After Effects was used to compile the exported ZBrush movie and Photoshop inset files, create and animate an action potential along the retinal ganglion cell inset image and 3D model x-section, and incorporate appropriate anatomical labels according to the script. Audio narration was recorded and incorporated into the final movie file as an .wav file using Adobe Audition CC 2021. The resulting animation was saved as a .MOV file and converted into a .MPG4 file using Adobe Media Encoder 2021.

Importing Animations into Unity3D

To import the animations into Unity, a render texture was created through Assets > Create > Render Texture within the same folder the animation file was imported. This generated a Video Output method for the animation. Within the render texture Inspector, the size was adjusted to match the dimensions of the video animation to be imported.

Next, a new empty GameObject was created in the hierarchy, with "Video Player" component activated. The desired video clip was then assigned into the Video Player>Video Clip" hierarchy within the inspector (Figure 51). The render texture was also selected inthe Video Player>Render Mode settings of the "Video Player" inspector.

A "Raw Image" was then placed on the Canvas. Within the "Texture" field in the Inspector, the render texture file was dragged in. This allowed the Video Player to reference the animation and apply it to the texture.

Getting the animation to pause and play involved several elements. The first was having the toggle button on the hand controller govern fundamental features necessary to pause and play. Within the "Video Player" GameObject Inspector, a component was added with an assigned script to dictate conditions upon which the toggle initiates pausing and playing. One of the functions utilizes the "Playback Speed" within the Video Player Inspector, which was set to "0" to establish the pause speed (Figure 51). Finally, a script function was assigned to the "On Click" component in the Inspector to dictate the conditional actions of the toggle button.

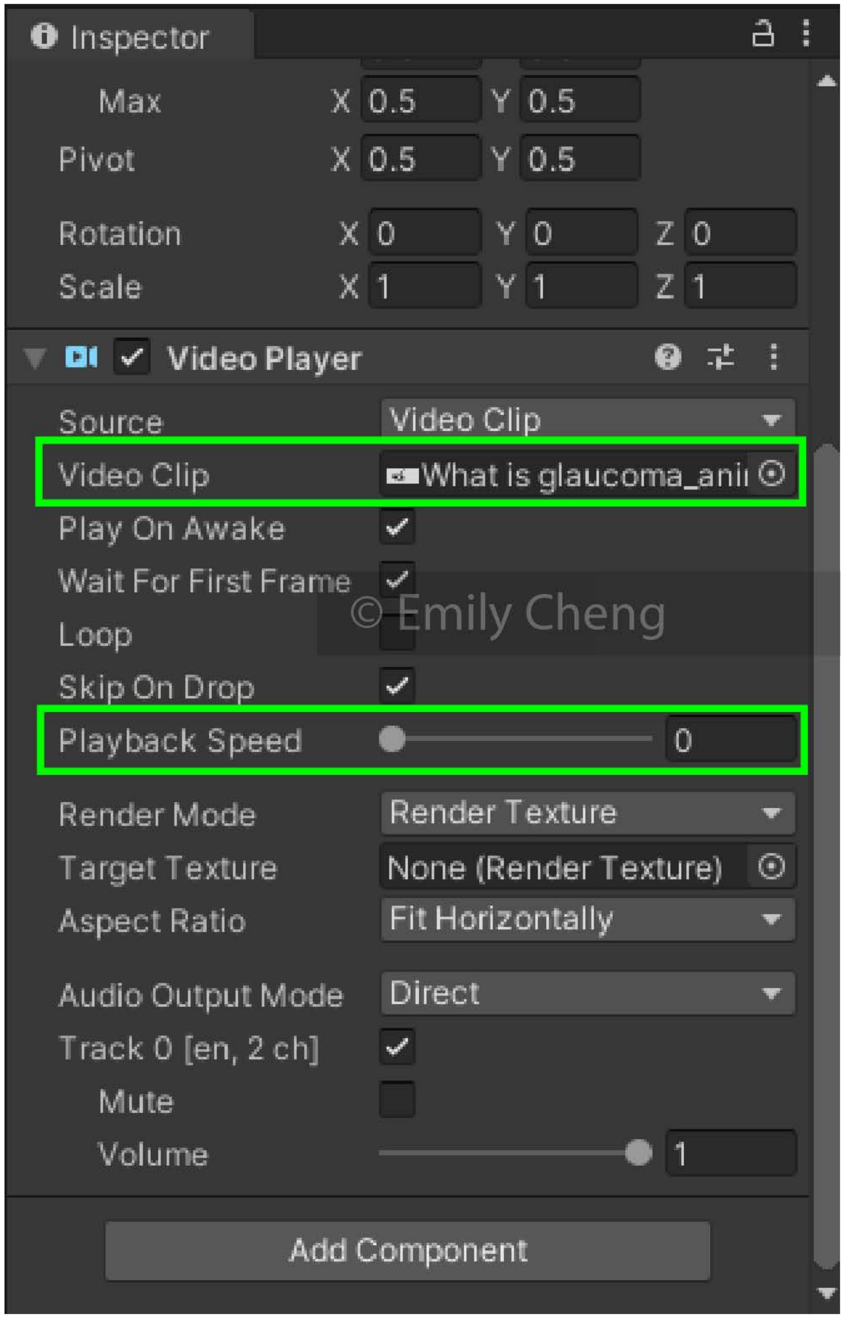


Figure 51. *Applying Video Renderer and Modifying Playback Speed.*

Workflow for Exporting Low Poly Assets from High Poly Models in ZBrush

High polygon count models made in ZBrush are typically not fit for use within game engines, as they can negatively affect render performance. The best practice is to create a lower polygon version that is paired with mapped textures containing **normal, diffuse, ambient occlusion** and **displacement** maps. To obtain these files, the finalized high polygon version of the 3D models (including Polypaint details) were saved as separate Subtools. Each Subtool was then duplicated and made into a low polygon count 3D model using Geometry > ZRemesher (Figure 52A). Upon completion, it was subdivided, using Geometry > Divide, into a suitable polycount (in this case 6 times) (Figure 52B). The original high-poly mesh version (including sculpted details and color information) was then projected onto the new lower poly mesh version at its highest subdivision level using Subtool > Project > ProjectAll. This procedure captured all of the detail of the high poly model into the lower poly clone (Figure 52C). Each of the three models were subsequently prepared and prepped for export into Unity.

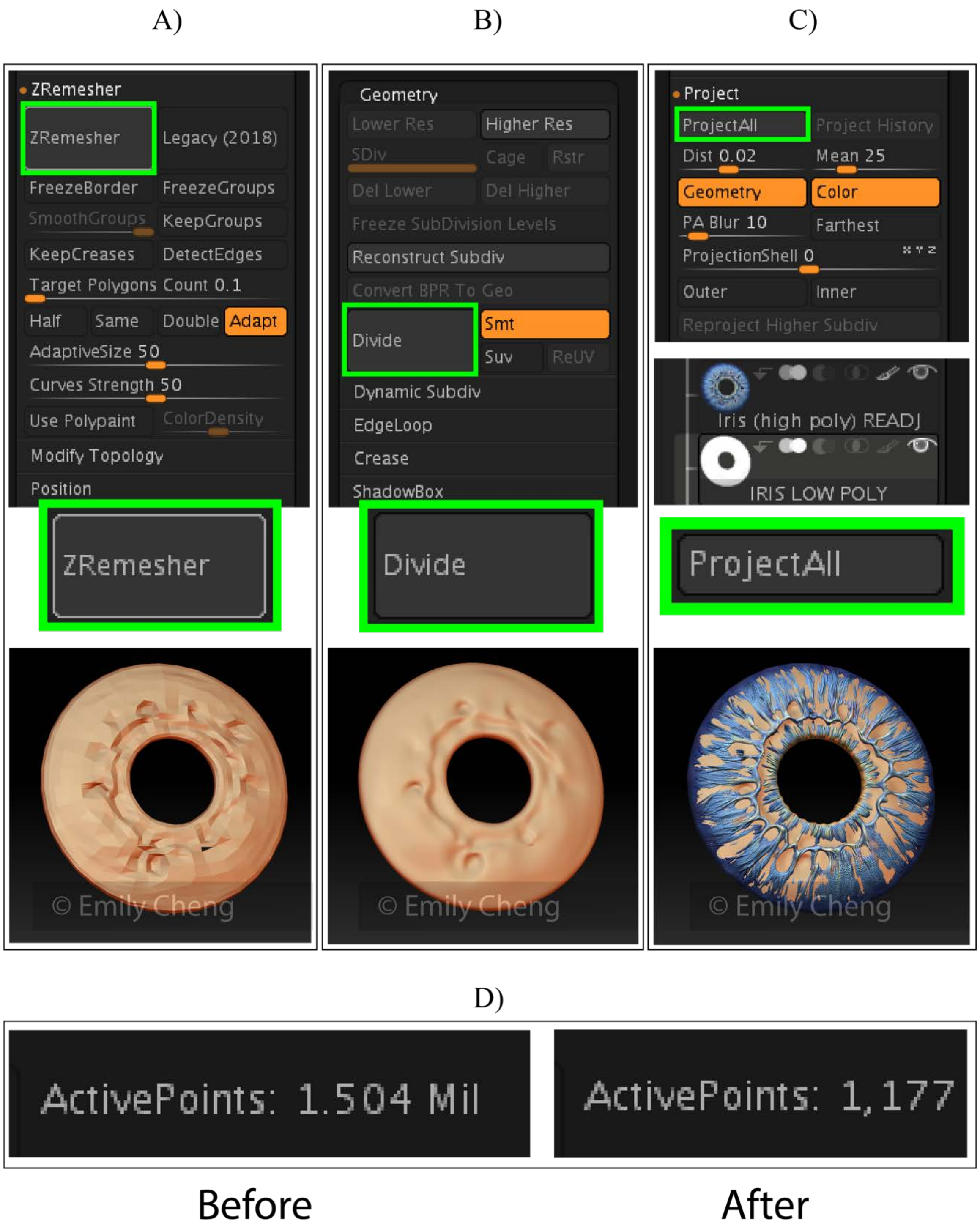


Figure 52. *Screenshots of ZRemesher, Divide, ProjectAll features within ZBrush Interface. (A) ZRemesher and resulting ZRemeshed example Iris (B) Subdivision and resulting subdivided Iris (C) ProjectAll with both original high-polygon iris and low polygon duplicate visible. (D) Before and after polygon count between low and high poly irises.*

Exporting OBJs with Displacement, Normal, Polypaint Texture and Ambient Occlusion Maps for Import into Unity3D

In order to prepare all three of the low poly models of the eyes for import into Unity, each model was UV unwrapped using ZPlugin> **UV Master** at their lowest subdivision level. The ZPlugin **Multi Map Exporter** was then used to export out the low poly mesh OBJs and all of the different types of maps for Import into Unity. With the desired map options selected (Displacement, Normal, Texture from Polypaint, Ambient Occlusion and Export Mesh), the **Create All Maps** button was selected (Figure 53). The end result are multiple maps (Figure 54) that allow a low poly mesh model to look exactly like the high poly count sculpt.

Figure 53. UV Master Unwrap and Multi-map Exporter Menus.

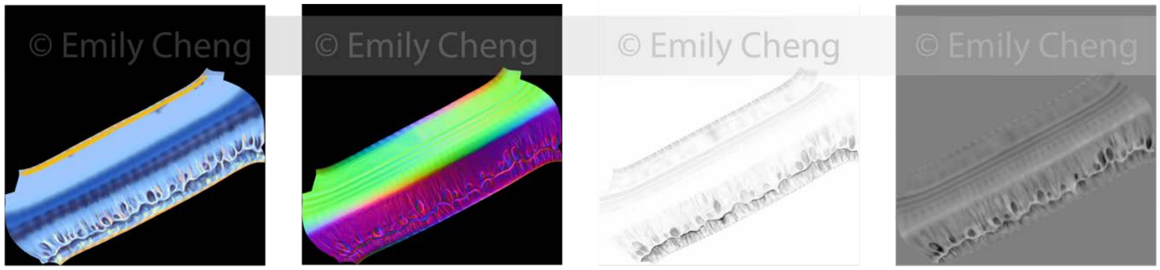


Figure 54. *Example ZBrush Map Exports of the Iris.*

Rendering in Unity3D

A scriptable render pipeline built by Unity, called the Universal Render Pipeline (URP), was used to render the scenes within this application. URP is installed from the Package Manager in the Windows option of the Unity menu. A "Pipeline Asset" was then created within the assets folder by selecting Create > Rendering > Universal Render Pipeline > Pipeline Asset. Any object that was not heavily interacted with was set as static within the inspector to reduce computing requirements.

Results

Phase 1: Patient Derived Data

Patient Visual Assessment Tool Assets

The following figures comprise the resulting prepared distortions that were globally presented to each patient during their initial session. The resulting patient image masks are derived based on modifying these prepared distortions. The distortions are arranged in layers and organized by regions (Figure 55). Figures 56 – 58 show the full image of the layer compositions for each task (Refer to Figure 16 in Materials and Methods). Figures 59-64 display the prepared global distortions that are then localized to the affected region based on patient description.

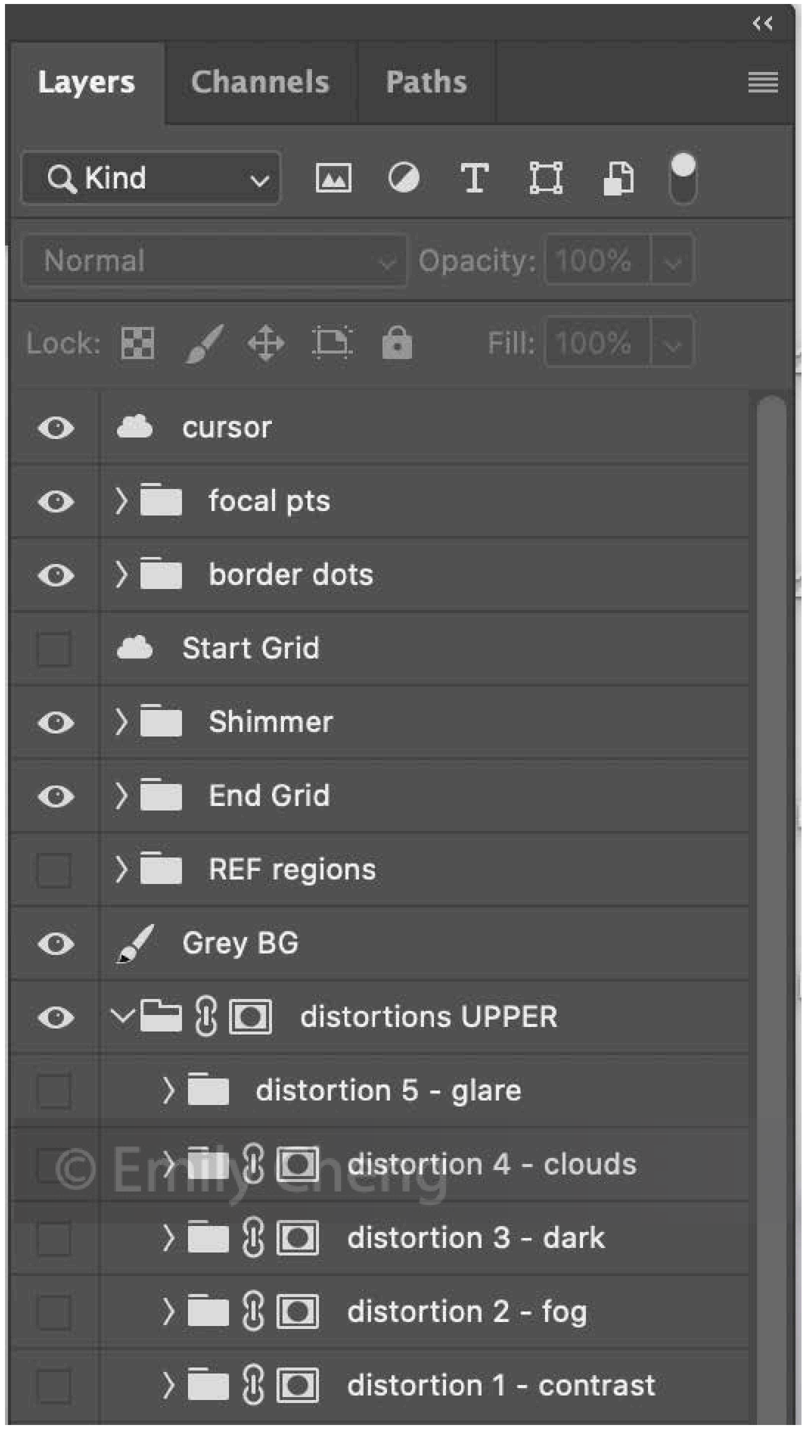


Figure 55A. *Upper Layer Composition of Visual Assessment Tool. Distortions are organized by upper, lower, and middle regions within the file.*

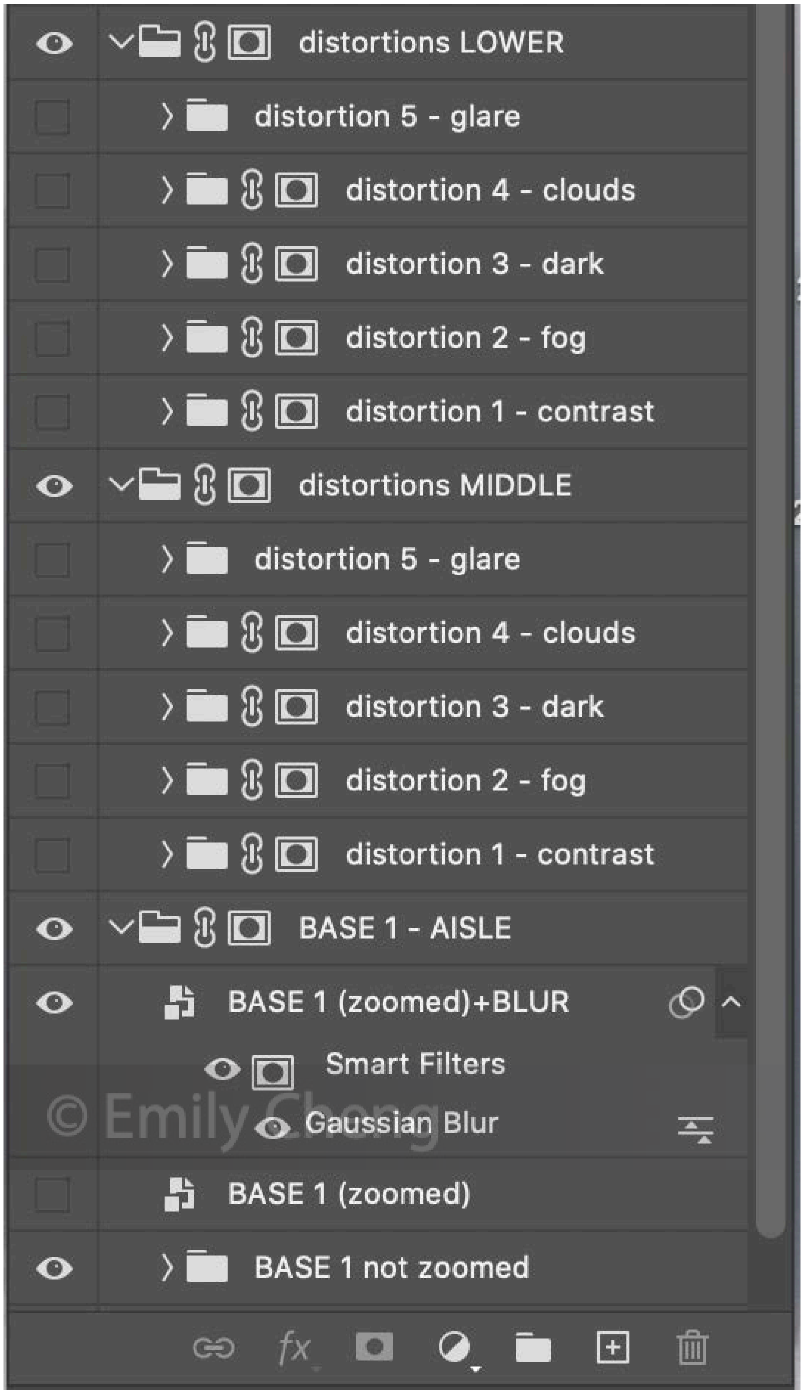


Figure 56B. *Lower Layer Composition of Visual Assessment Tool. Distortions are organized by upper, lower, and middle regions within the file.*

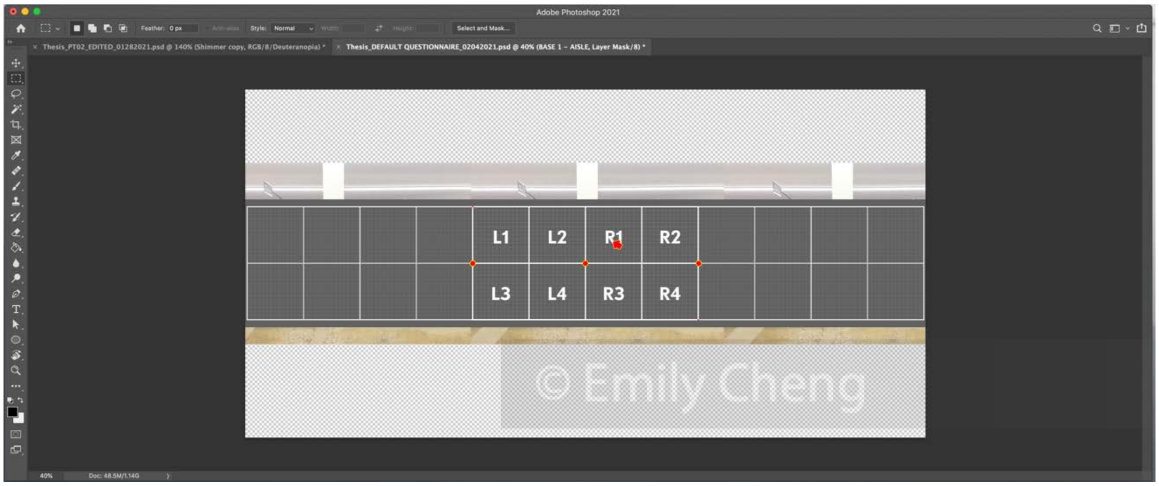


Figure 56. Intro Full file Layer Composition. Text not intended to be read.

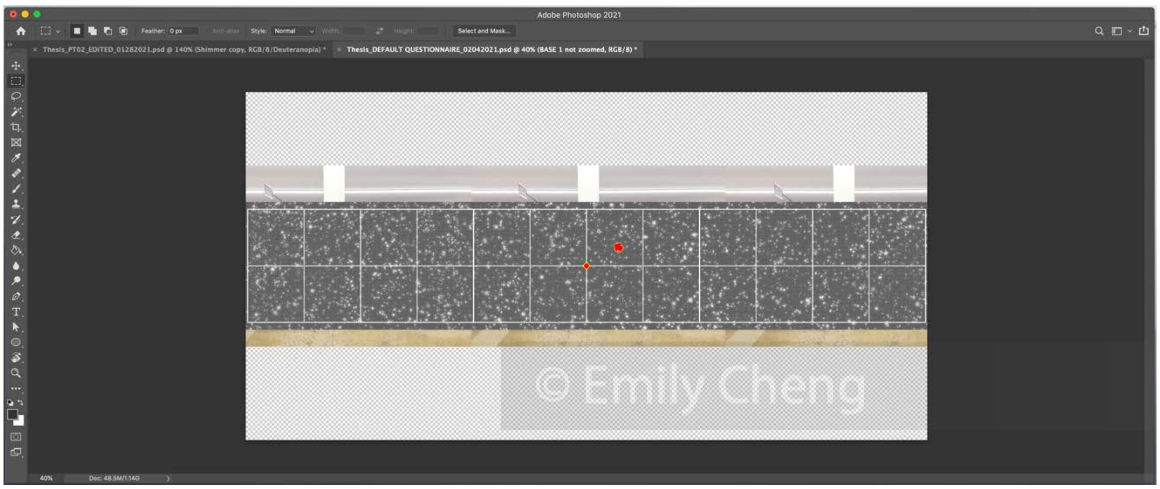


Figure 57. Shimmer Layer Composition. Text not intended to be read.

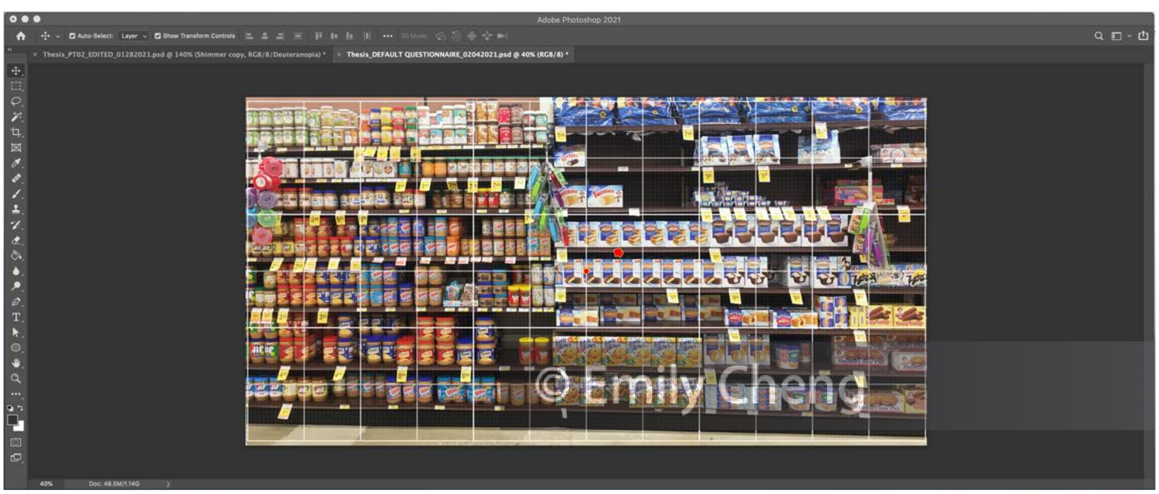


Figure 58. Grocery task Layer Composition. Text not intended to be read.

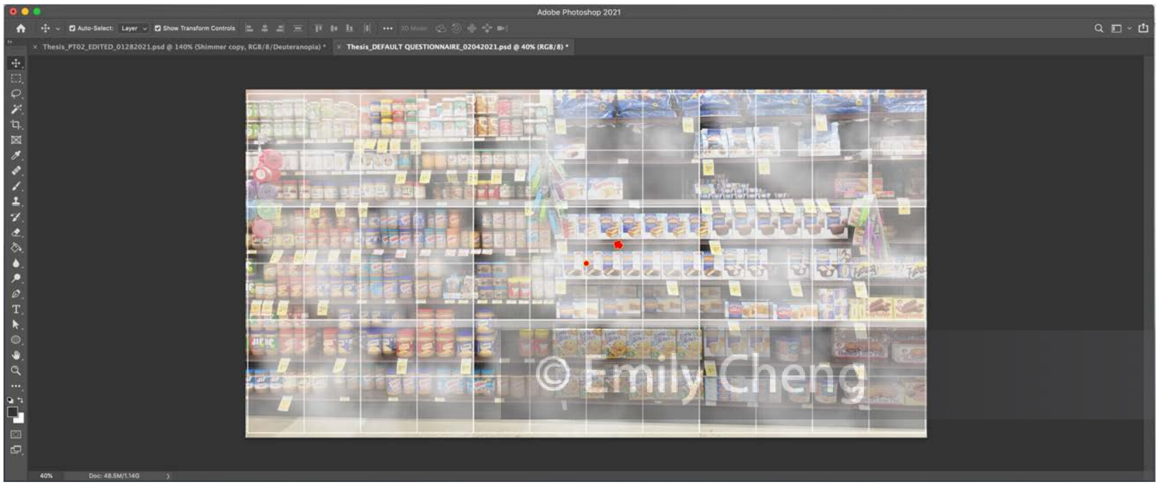


Figure 59. Global Cloudiness Distortion. Text not intended to be read.

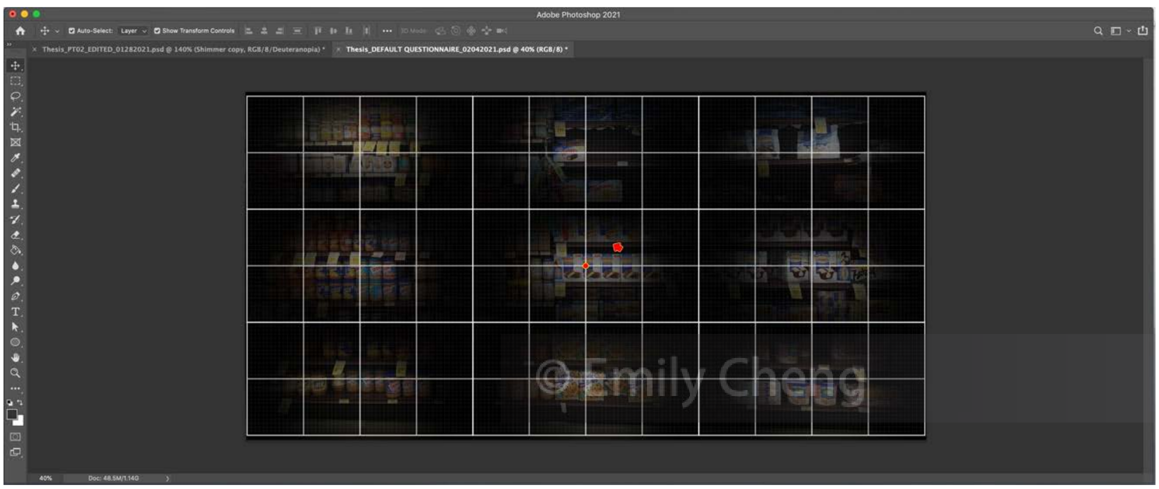


Figure 60. Global Darkness Distortion. Text not intended to be read.

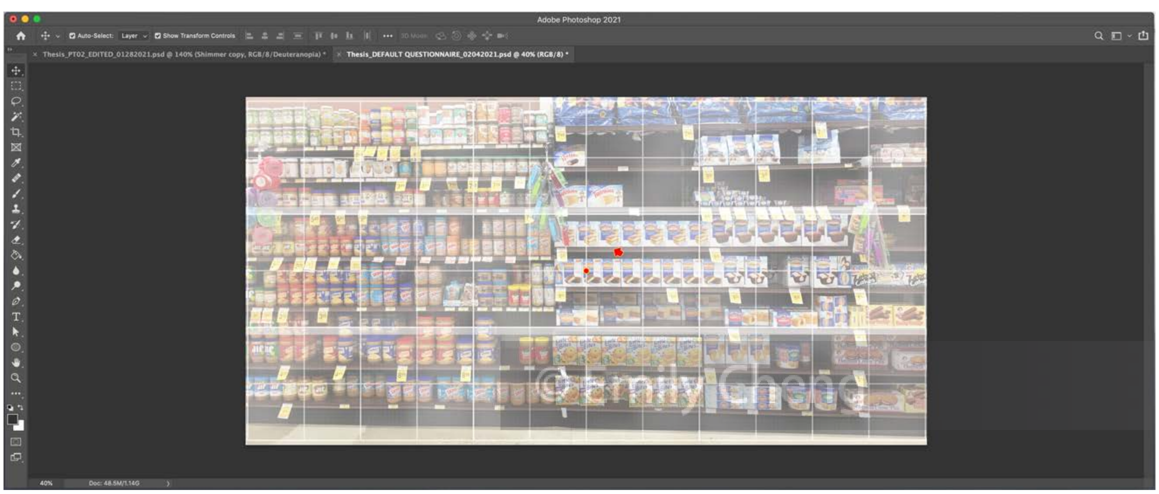


Figure 61. Global Fog Distortion. Text not intended to be read.

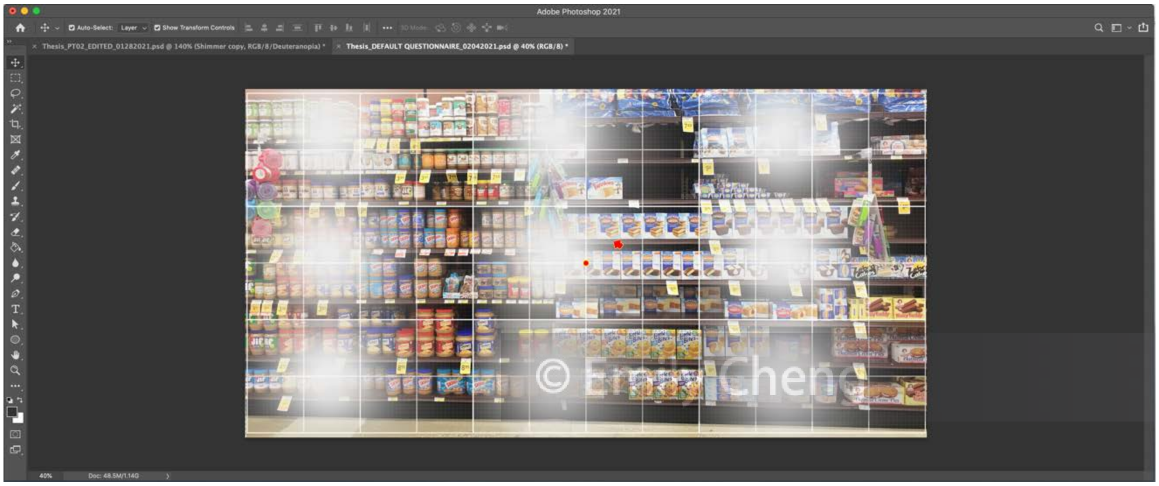


Figure 62. *Global Glare Distortion. Text not intended to be read.*

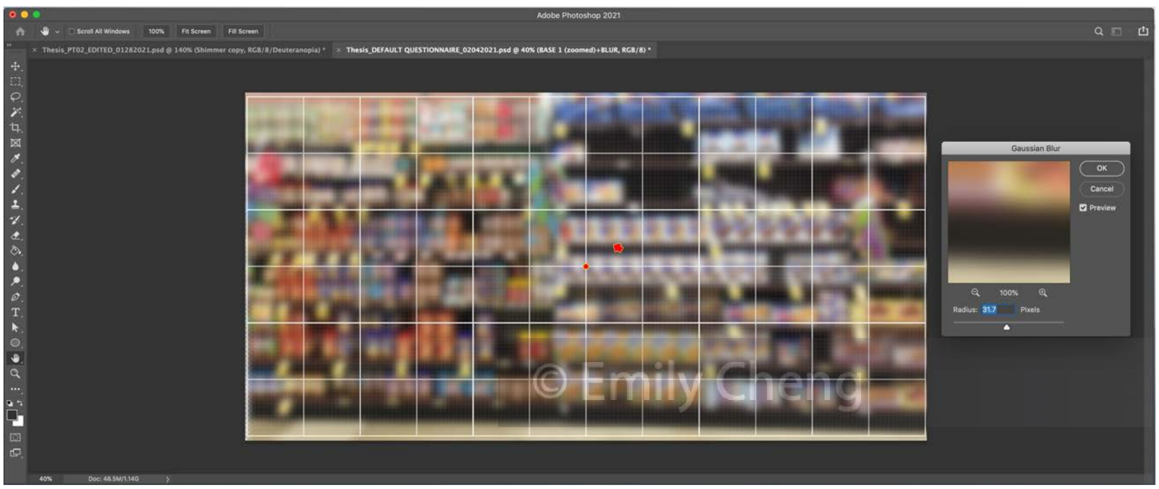


Figure 63. *Global Blur Distortion. Text not intended to be read.*

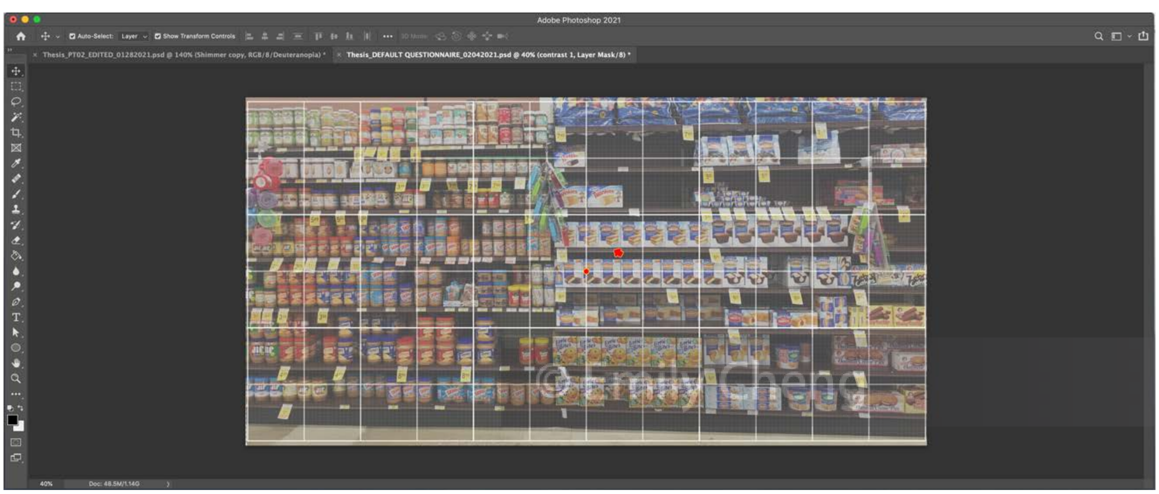


Figure 64. *Global Contrast Distortion. Text not intended to be read.*

Compilation of Resulting Masks to be Placed within Unity3D

Four patients were interviewed over the duration of this study. At least two sessions were held for each patient. A written report and initial session notes are presented in Appendix B. Resulting constructed image masks are presented at the dimensions originally projected on the 38" monitor.

Patient 01

Figure 65. *Patient 01 Final Image Mask Composition on Full Scene.*

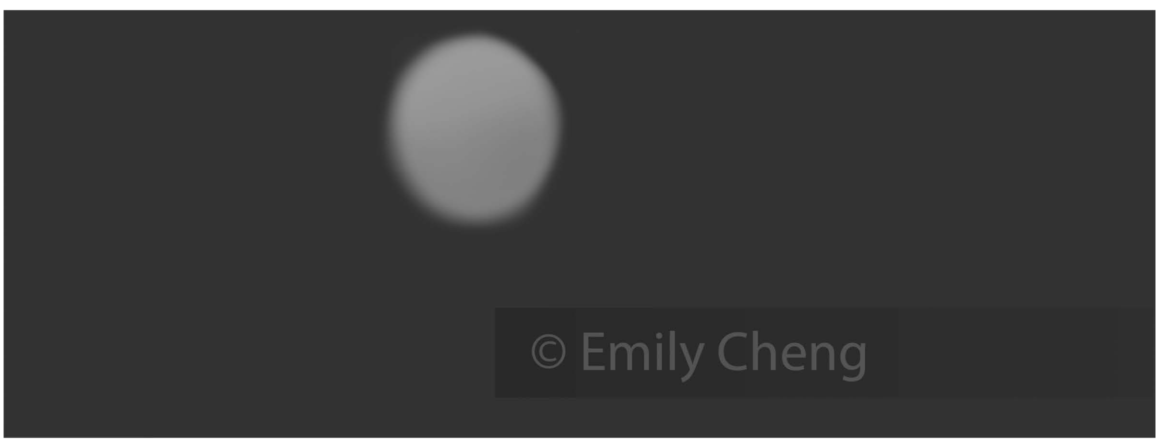


Figure 66. *Patient 01 Final Image Mask Composition Superimposed on Grey Background for Clarity.*

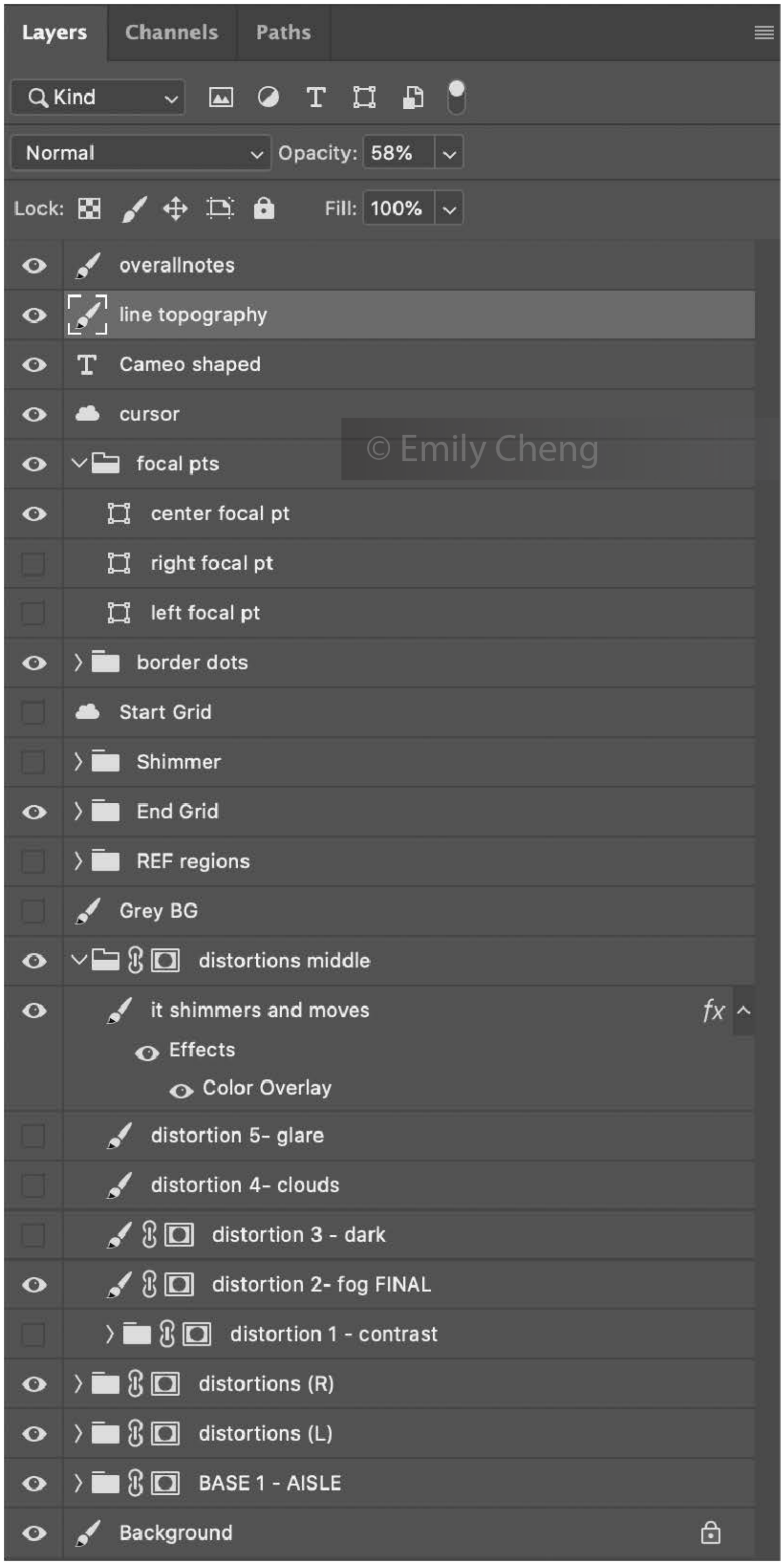


Figure 67. Patient 01 Final Layer Hierarchy for Developed Image Mask.

Patient 02

Figure 68. *Patient 02 Final Image Mask Composition on Full Scene.*

Figure 69. *Patient 02 Final Image Mask Composition Superimposed on Grey Background for Clarity.*

Figure 70. Patient 02 Final Image Mask View within Initial Projected Dimensions.

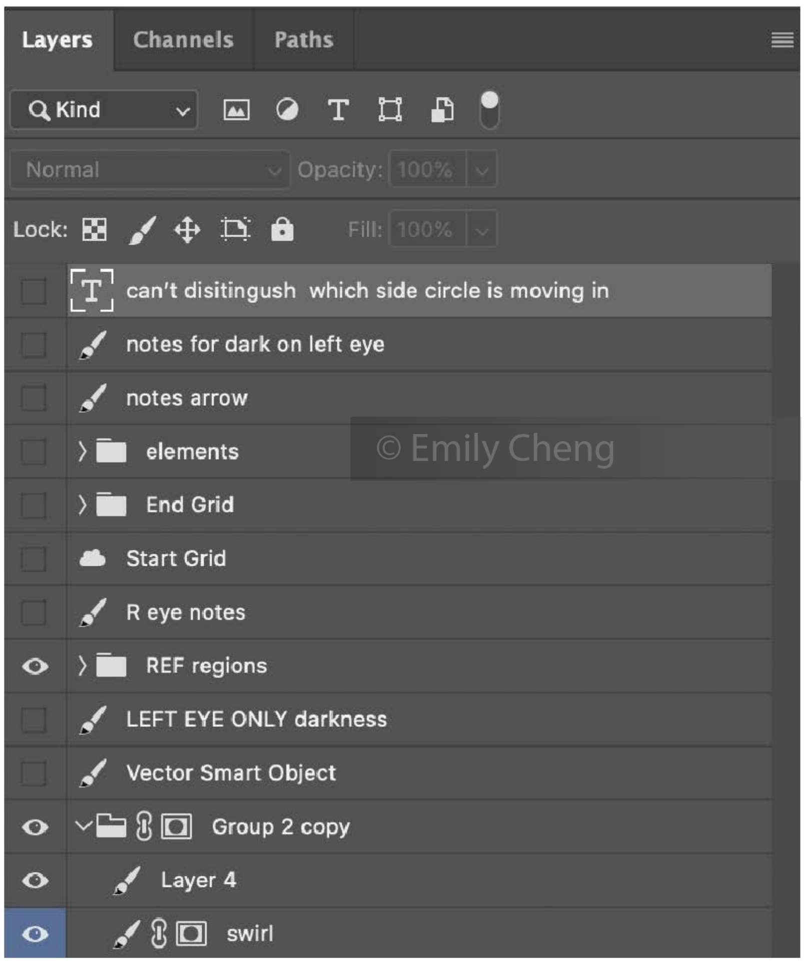


Figure 71A. Patient 02 01 Final Layer Hierarchy for Developed Image Mask Upper Layers

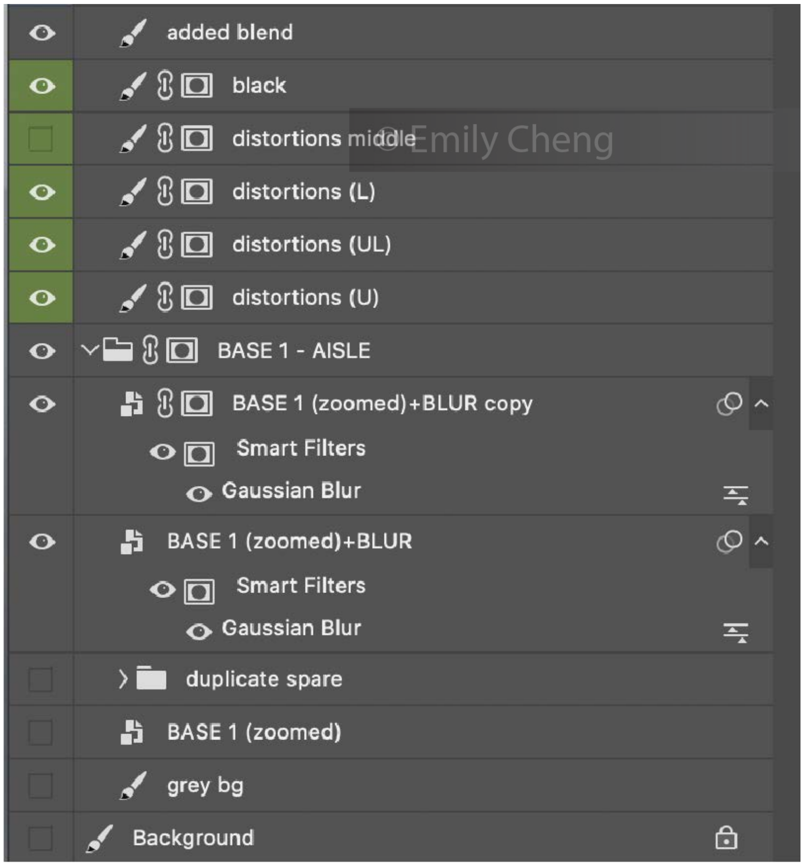


Figure 71B. *Patient 02 01 Final Layer Hierarchy for Developed Image Mask Lower Layers*

Patient 03

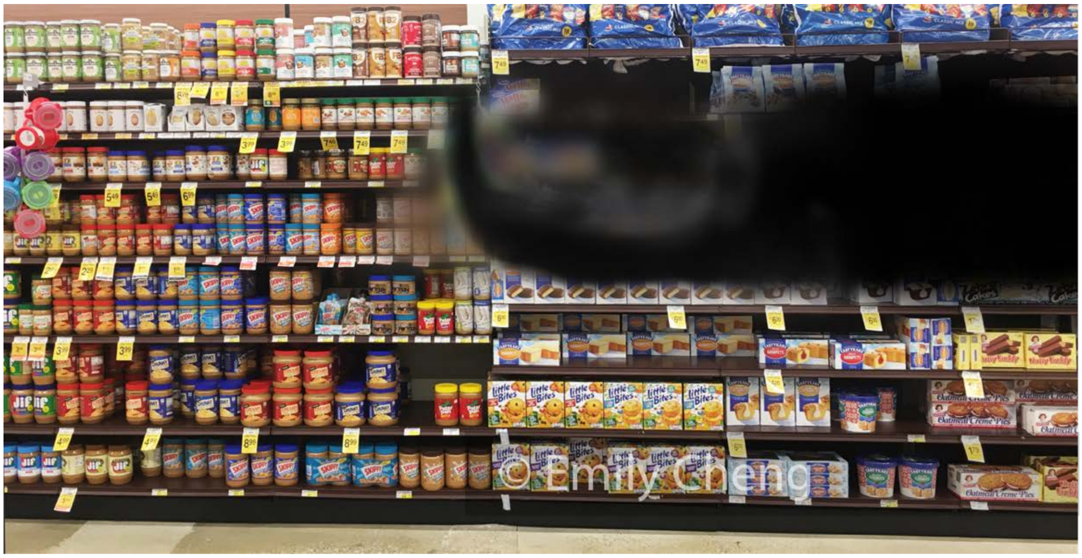


Figure 72. *Patient 03 Final Image Mask Composition on Full Scene.*

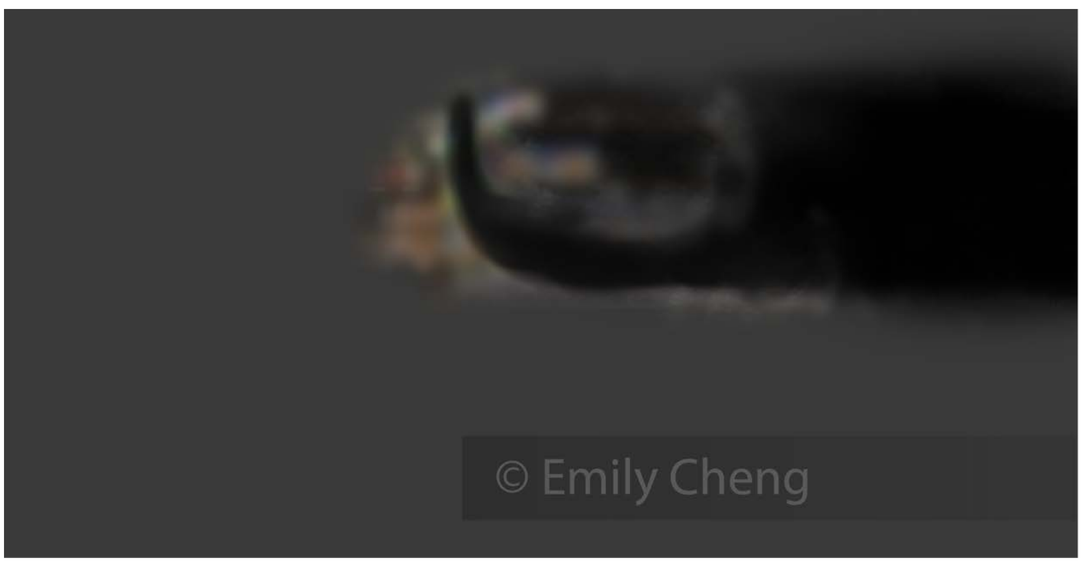


Figure 73. *Patient 03 Final Image Mask Composition Superimposed on Grey Background for Clarity.*

Figure 74. *Patient 03 Final Image Mask View within Initial Projected Dimensions.*

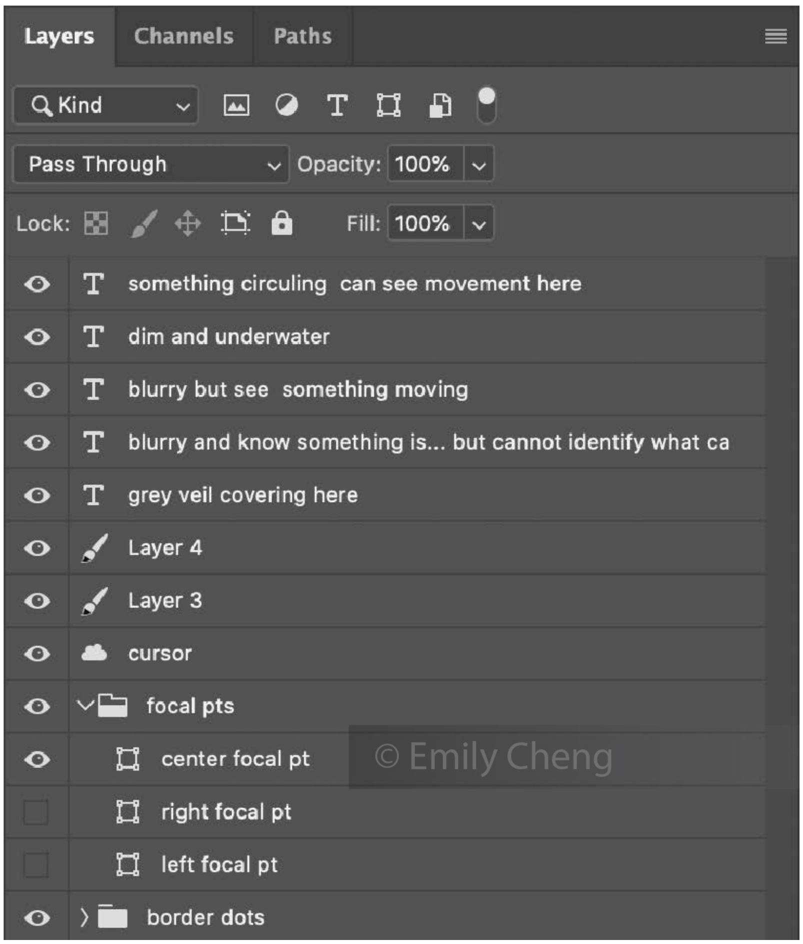


Figure 75A. *Patient 03 01 Final Layer Hierarchy for Developed Image Mask Upper Layers*

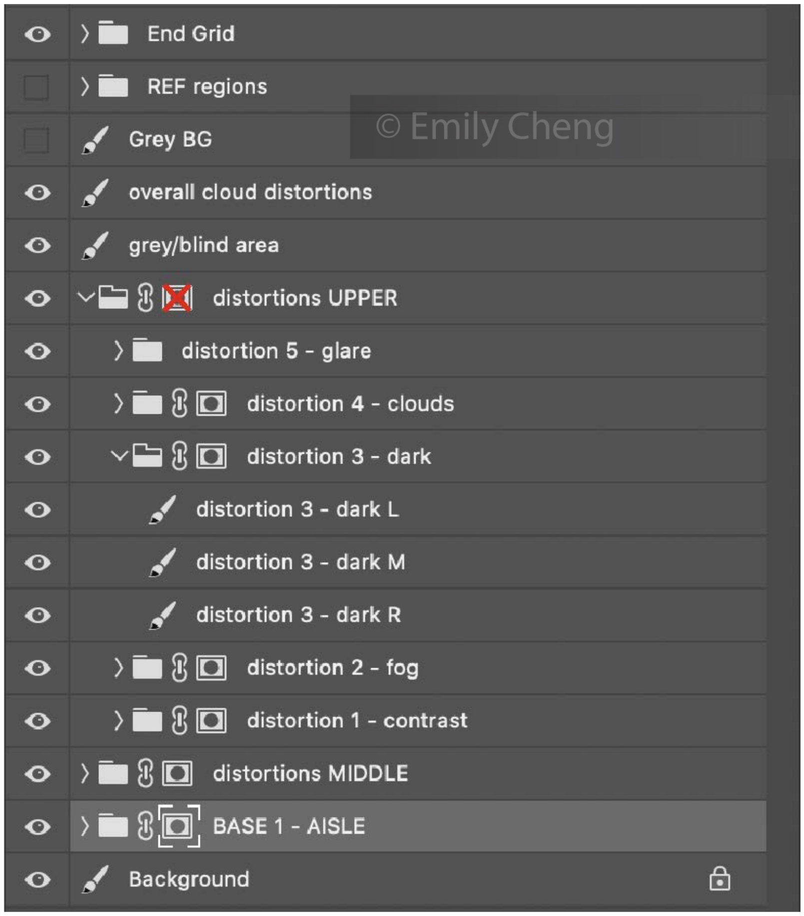


Figure 75B. *Patient 03 01 Final Layer Hierarchy for Developed Image Mask Lower Layers*

Patient 04

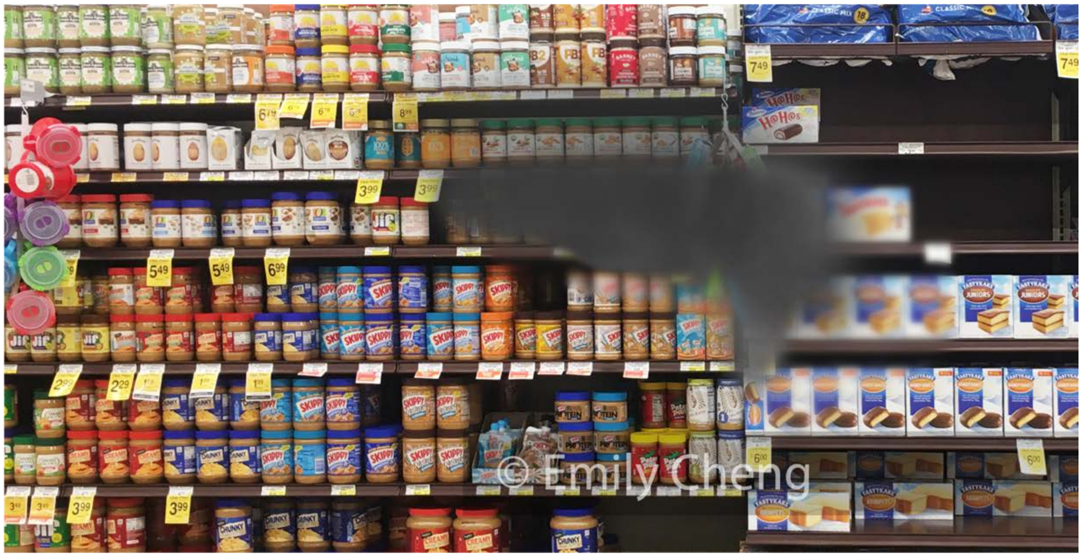


Figure 76. *Patient 04 Final Image Mask Composition on Full Scene.*

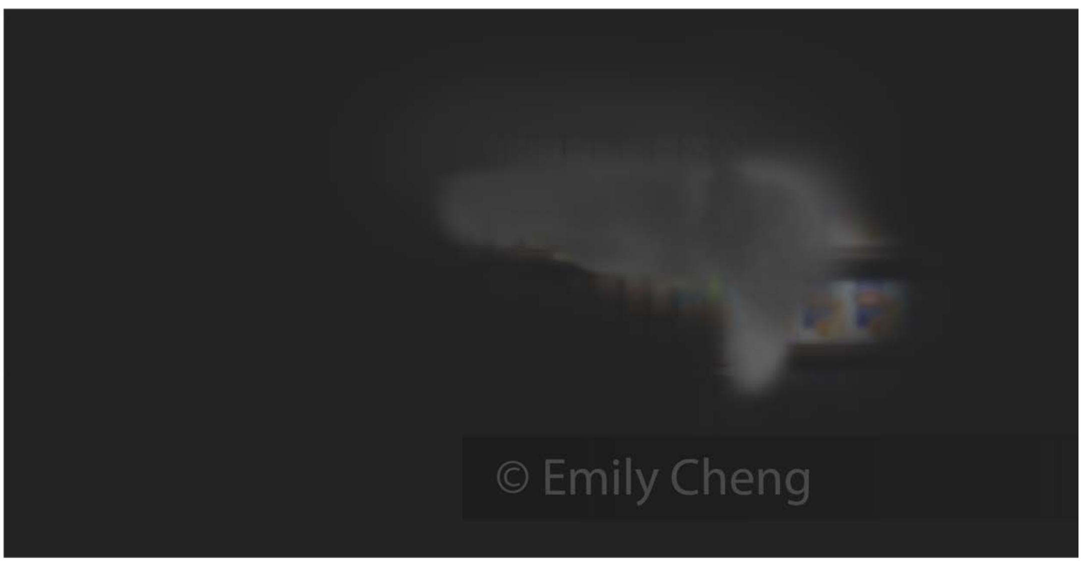


Figure 77. *Patient 04 Final Image Mask Composition Superimposed on Grey Background for Clarity.*

Figure 78. Patient 04 Final Image Mask View within Initial Projected Dimensions.

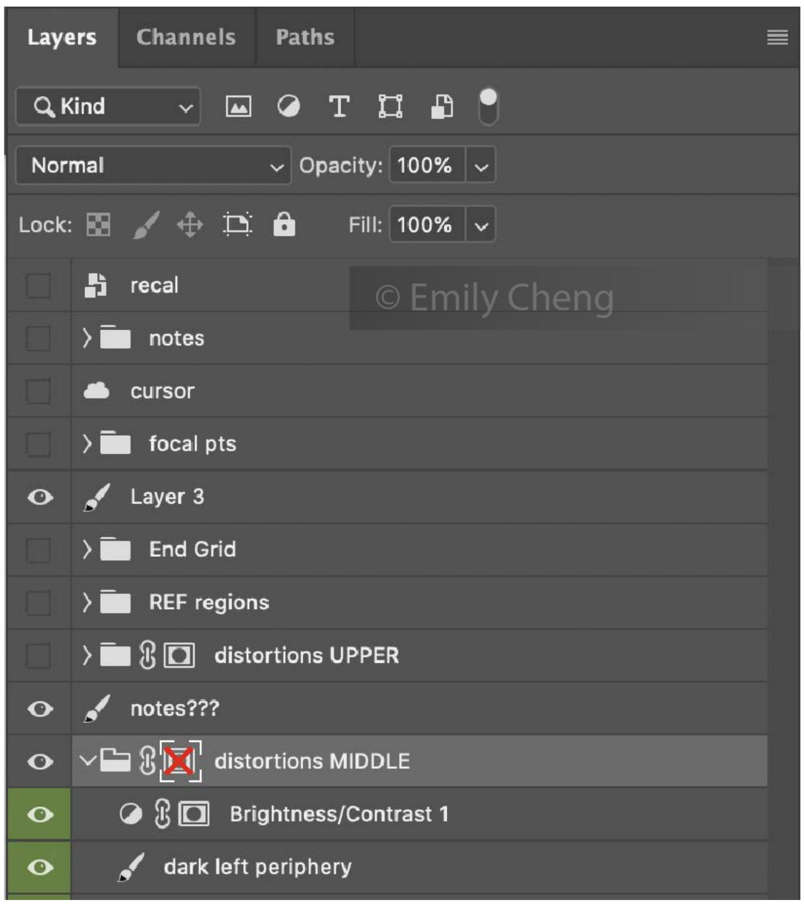


Figure 79A. *Patient 04 01 Final Layer Hierarchy for Developed Image Mask Upper Layers*

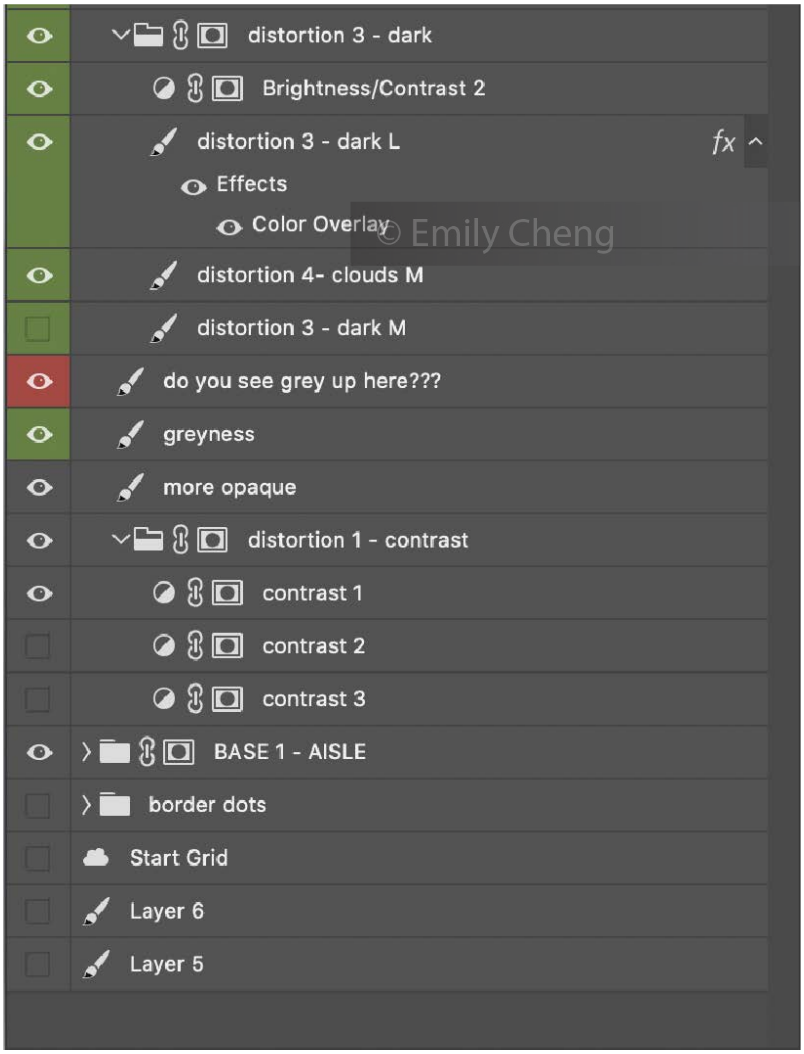


Figure 79B. *Patient 04 01 Final Layer Hierarchy for Developed Image Mask Lower Layers.*

Phase 2: Virtual Reality Application Assets

Main scene

Skybox Assets

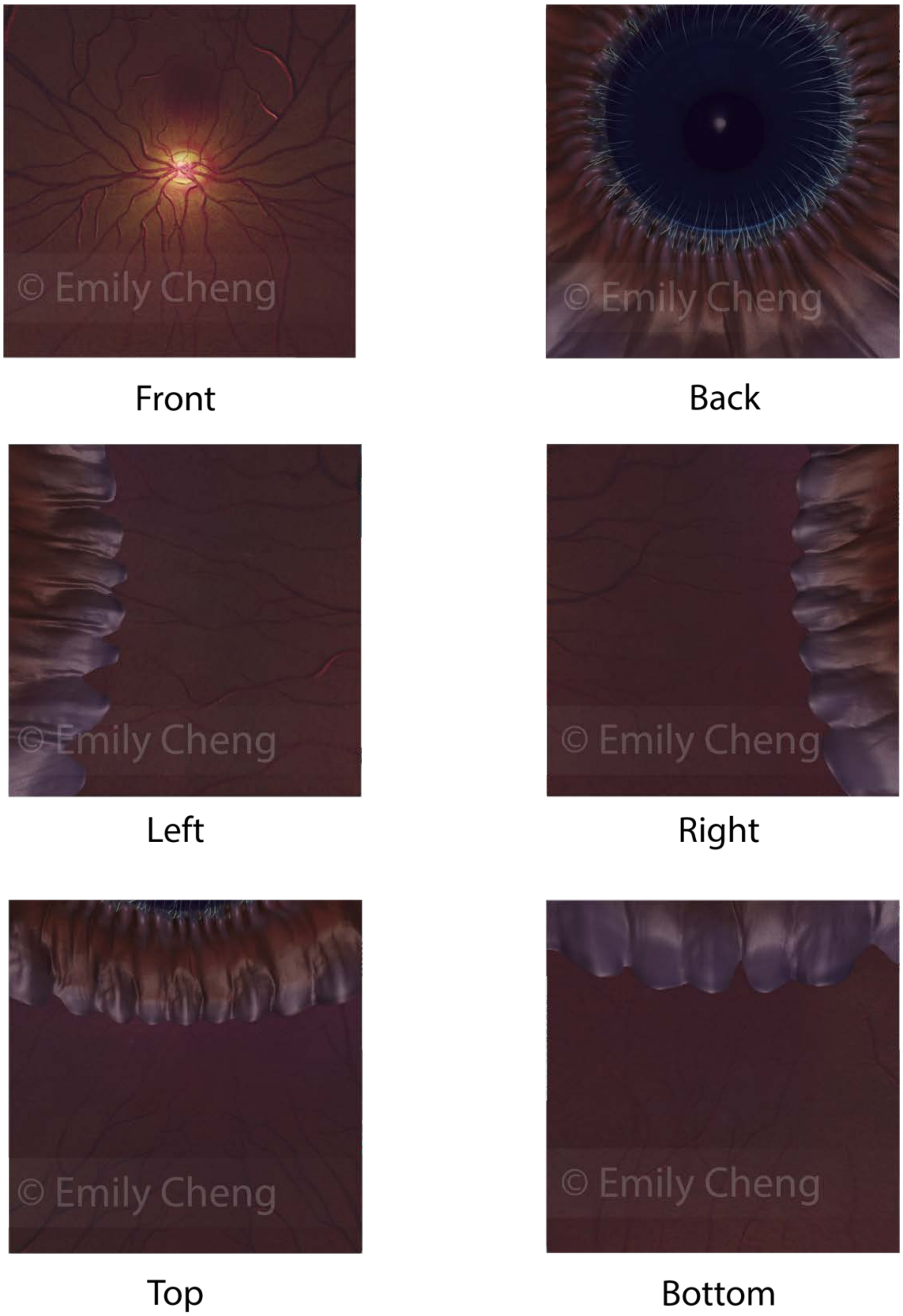


Figure 80. *Six Resulting Skybox Rendered Faces Rendered in Blender.*

VR Interaction with Main Page User Interface

Figure 81. *Initial View of Main Scene within Unity3D Interface. Text not intended to be read.*

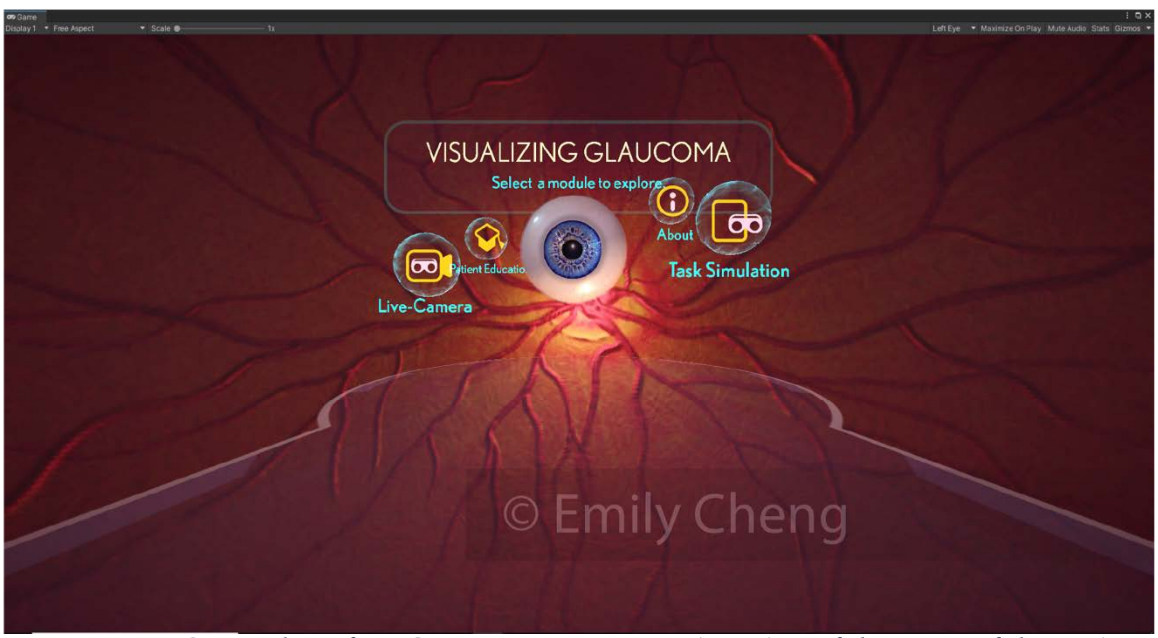


Figure 82. *Screenshot of HTC VIVE Pro Eye Inactive View of the Front of the Main Scene. Text not intended to be read.*

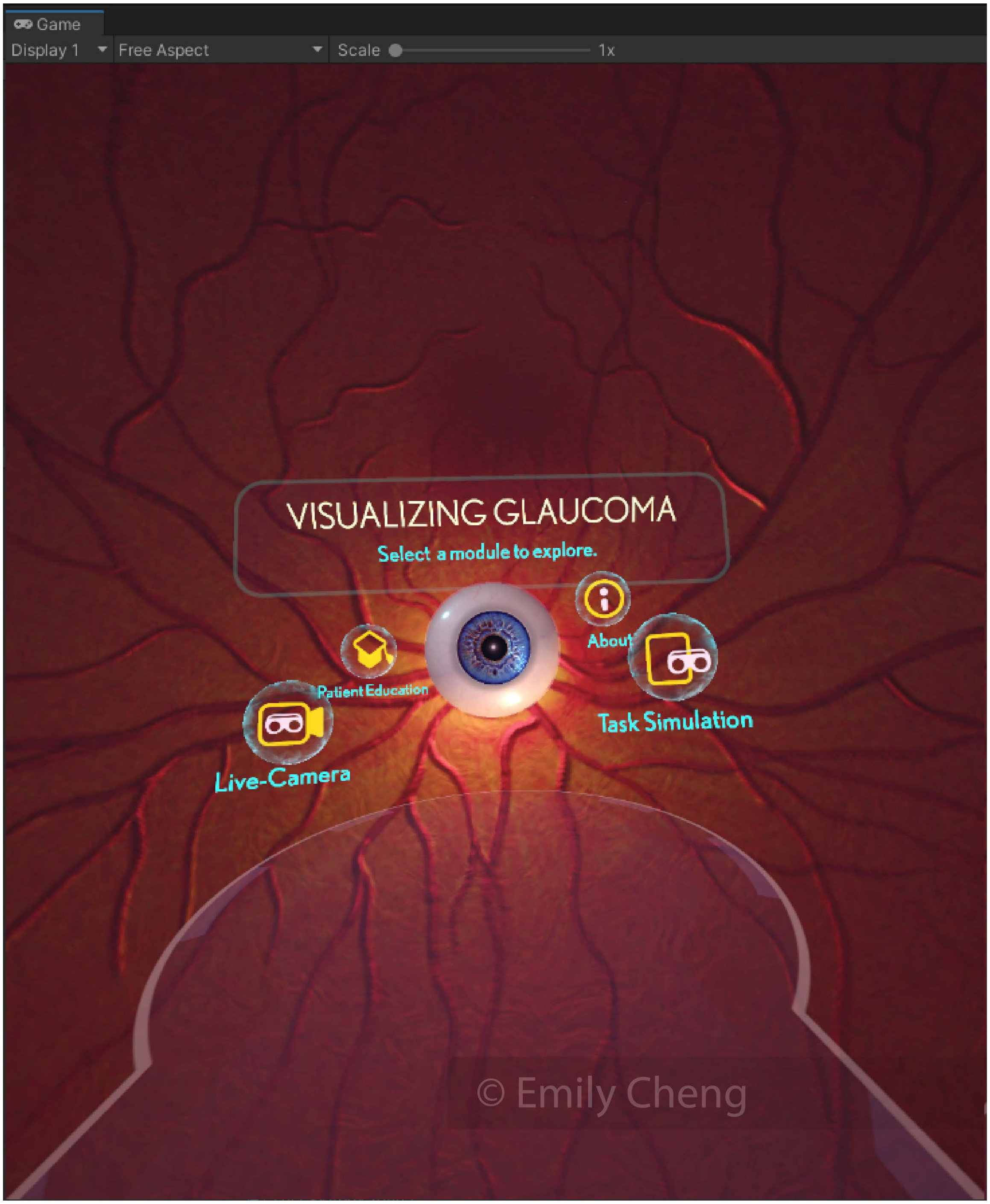


Figure 83. *Screenshot of HTC VIVE Pro Eye Active View of the Front of the Main Scene. Text not intended to be read.*

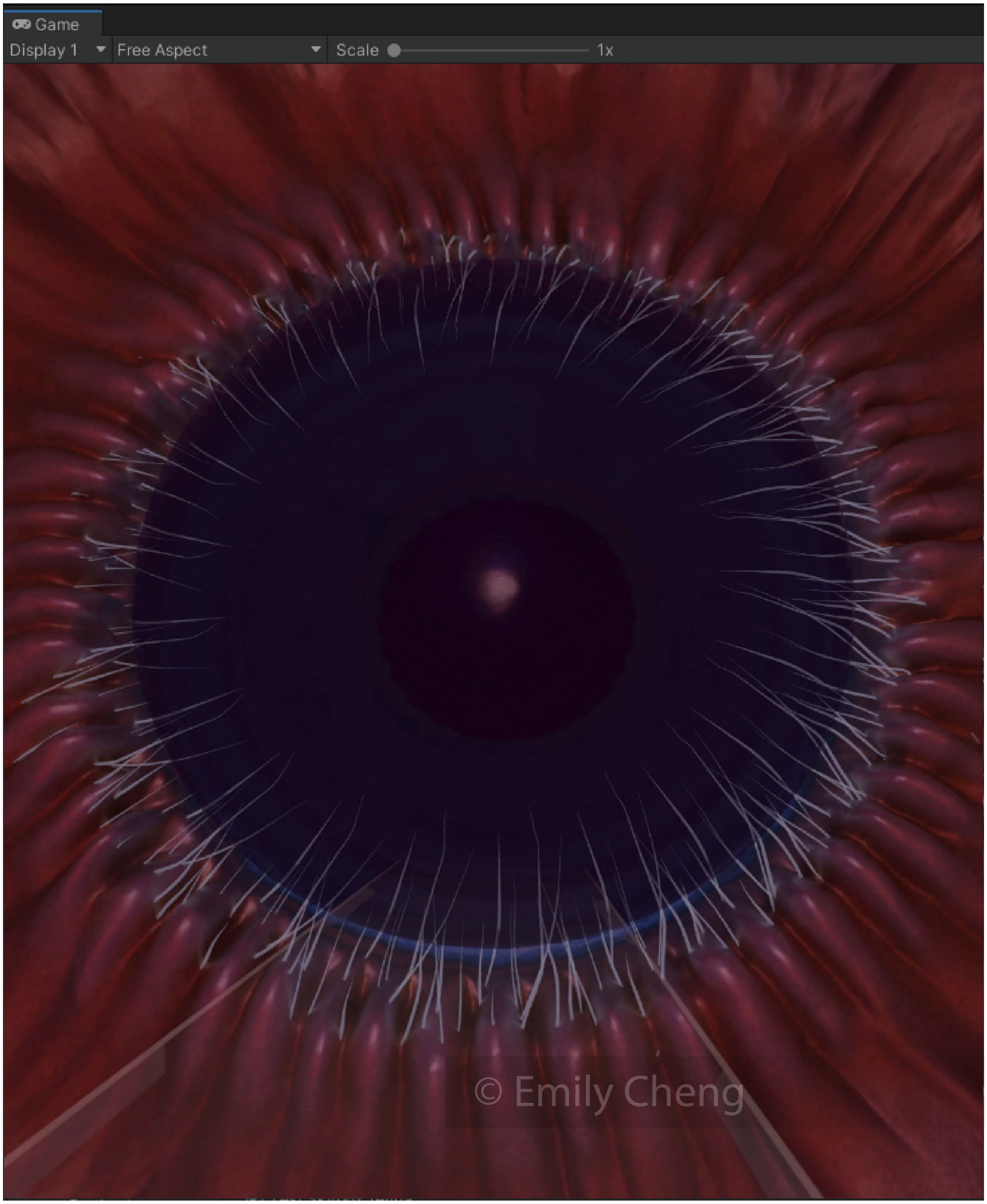


Figure 84. *Screenshot of HTC VIVE Pro Eye Active View of the Back of the Main Scene.*

Live-Camera Module

VR Interaction

The overall design of the user interface, along with the features that provide the user access to patient glaucoma distortions and information, is projected within the live-camera simulation. This same interface is also made available within the Search Task Simulator Module and can be referred to in the flowchart (Figure 117C).

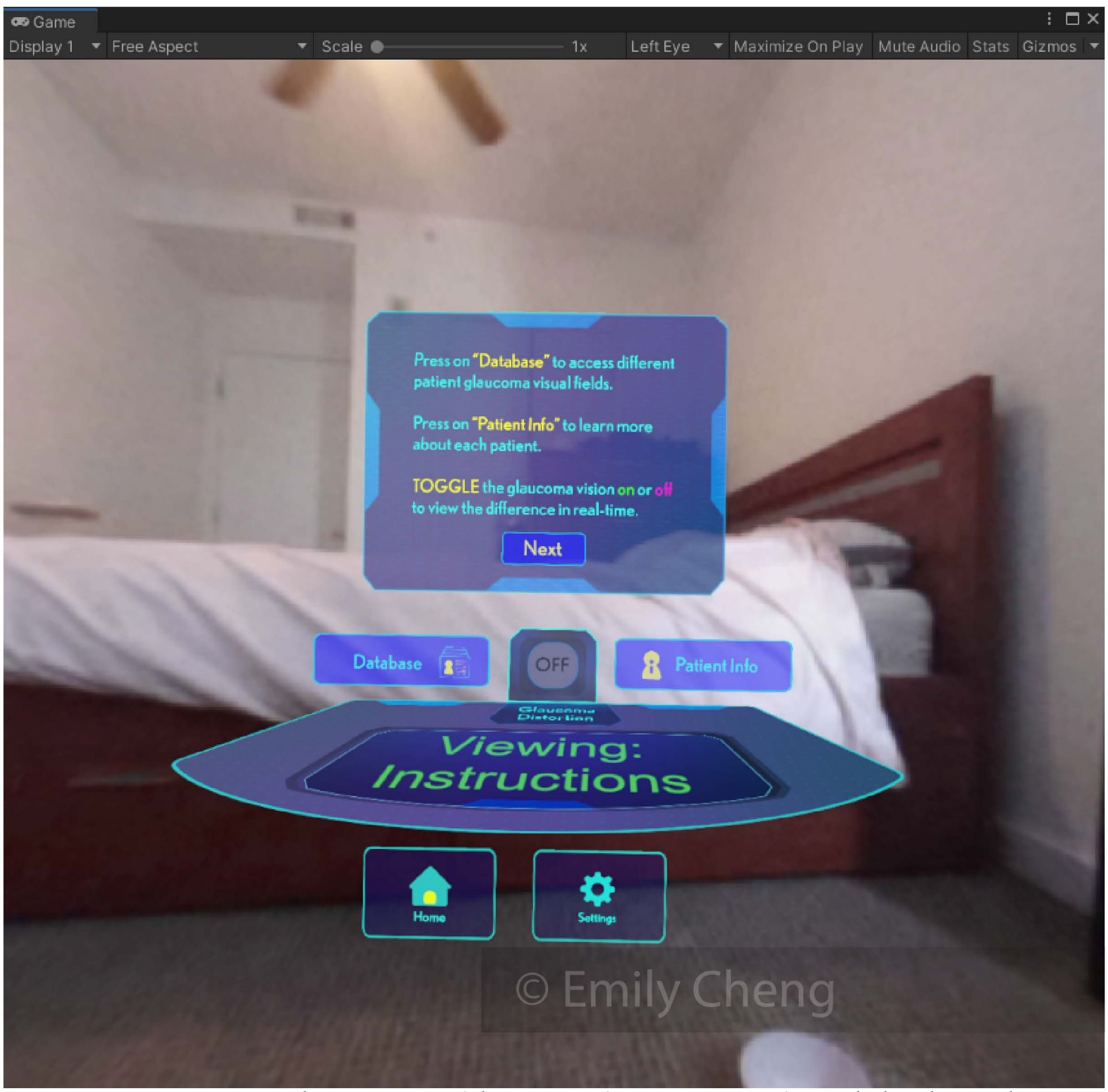


Figure 85. Introductory UI with Instructions. Text not intended to be read.

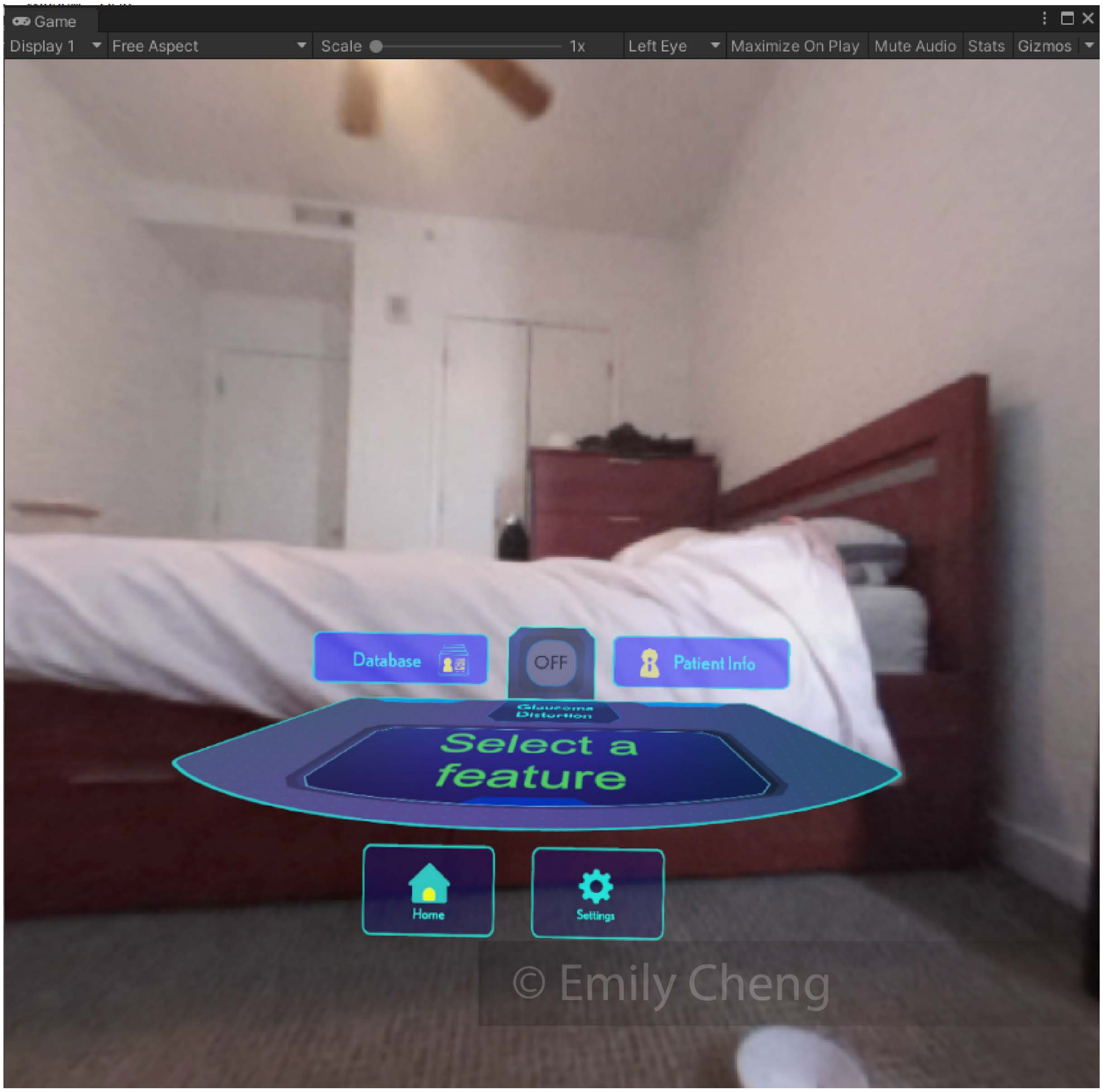


Figure 86. *UI with all Accessible Features Toggled Off. Text not intended to be read.*

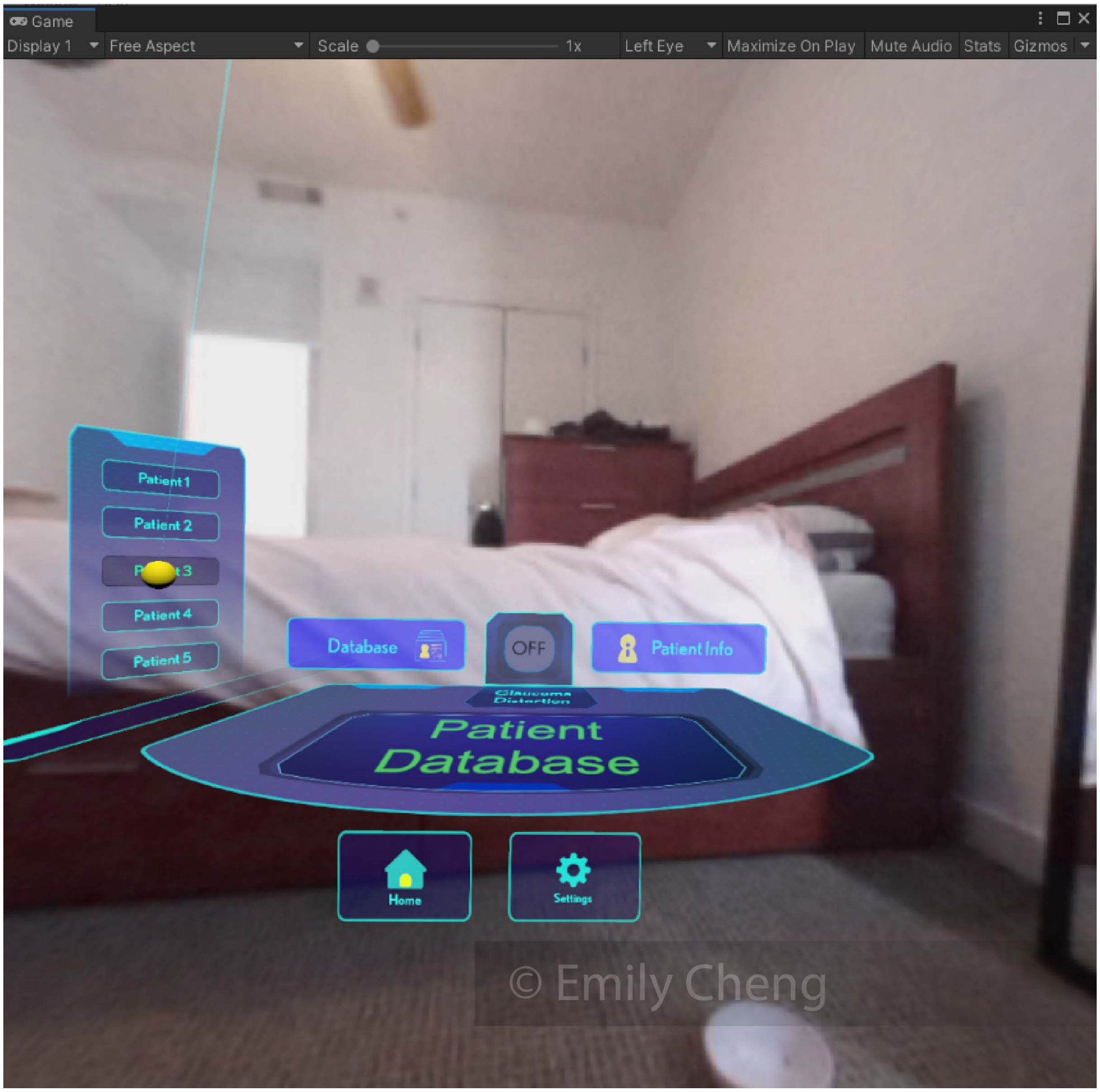


Figure 87. *UI with Database Feature Toggled On. Text not intended to be read.*

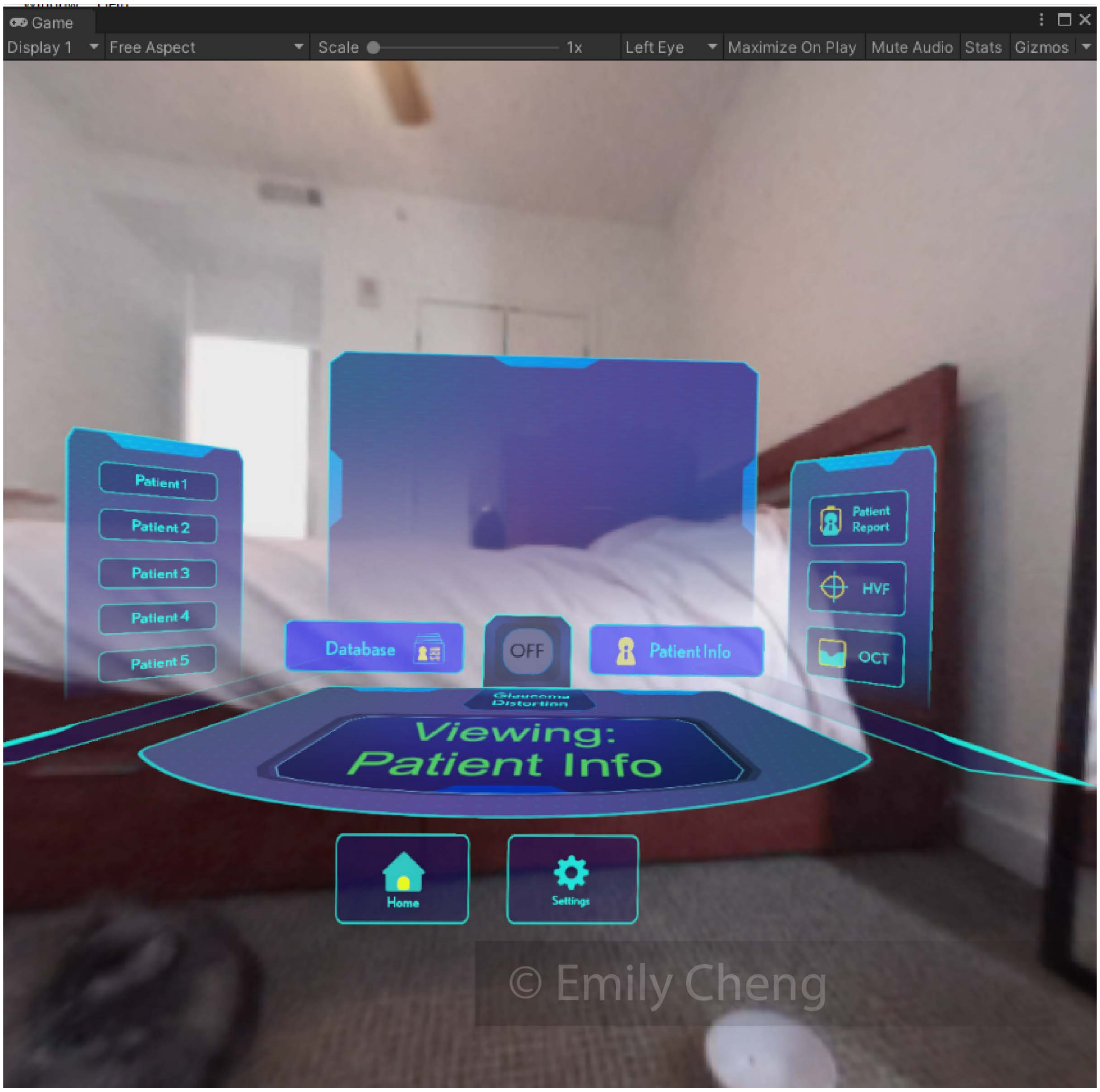


Figure 88. UI with Patient Database and Patient Info Features Toggled On. Text not intended to be read.

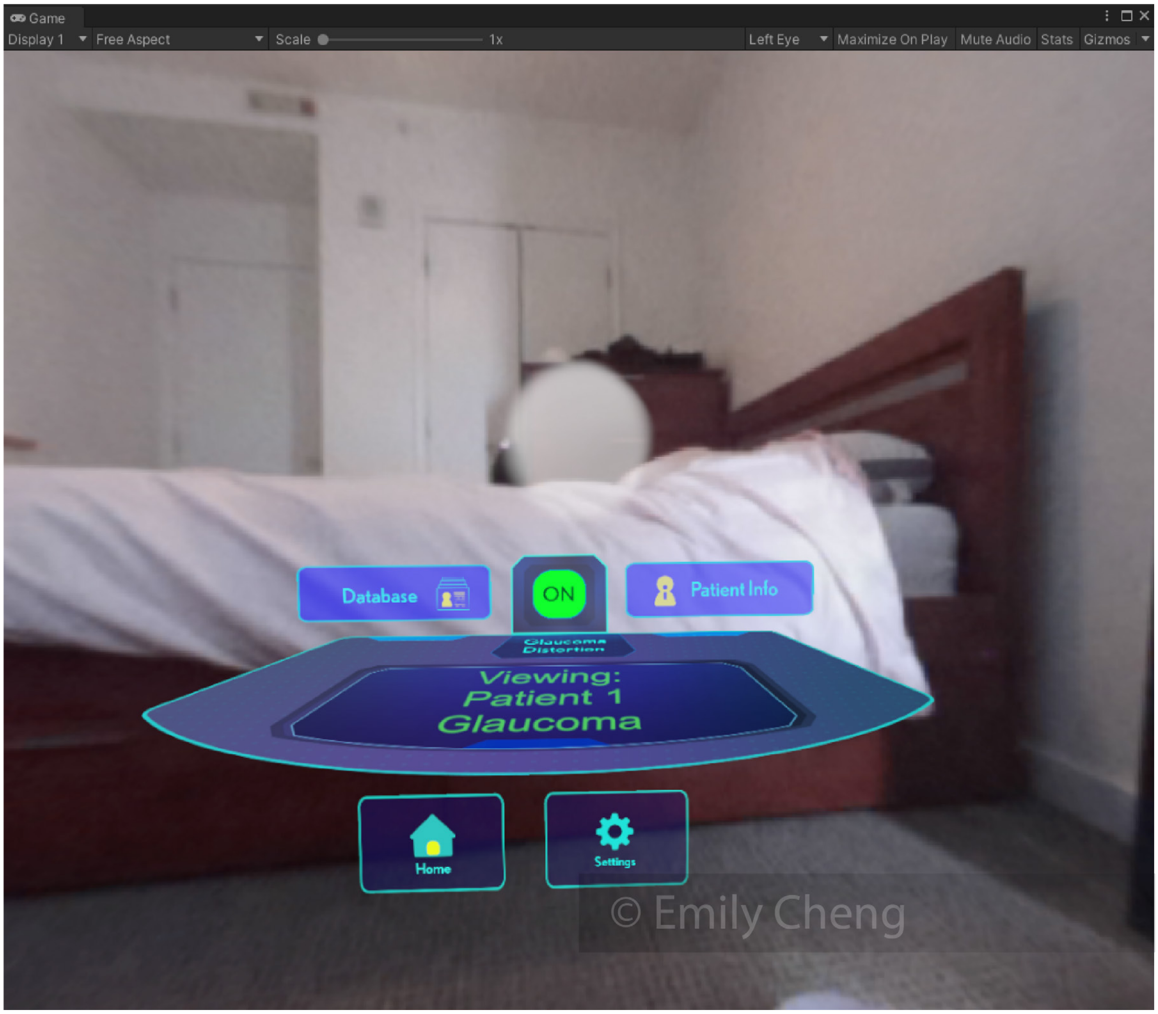


Figure 89. *UI with Only Glaucoma Distortion Toggled On Displaying Patient 01 Distortion. Text not intended to be read.*

Figure 90. *UI with Only Glaucoma Distortion Toggled On Displaying Patient 02 Distortion. Text not intended to be read.*

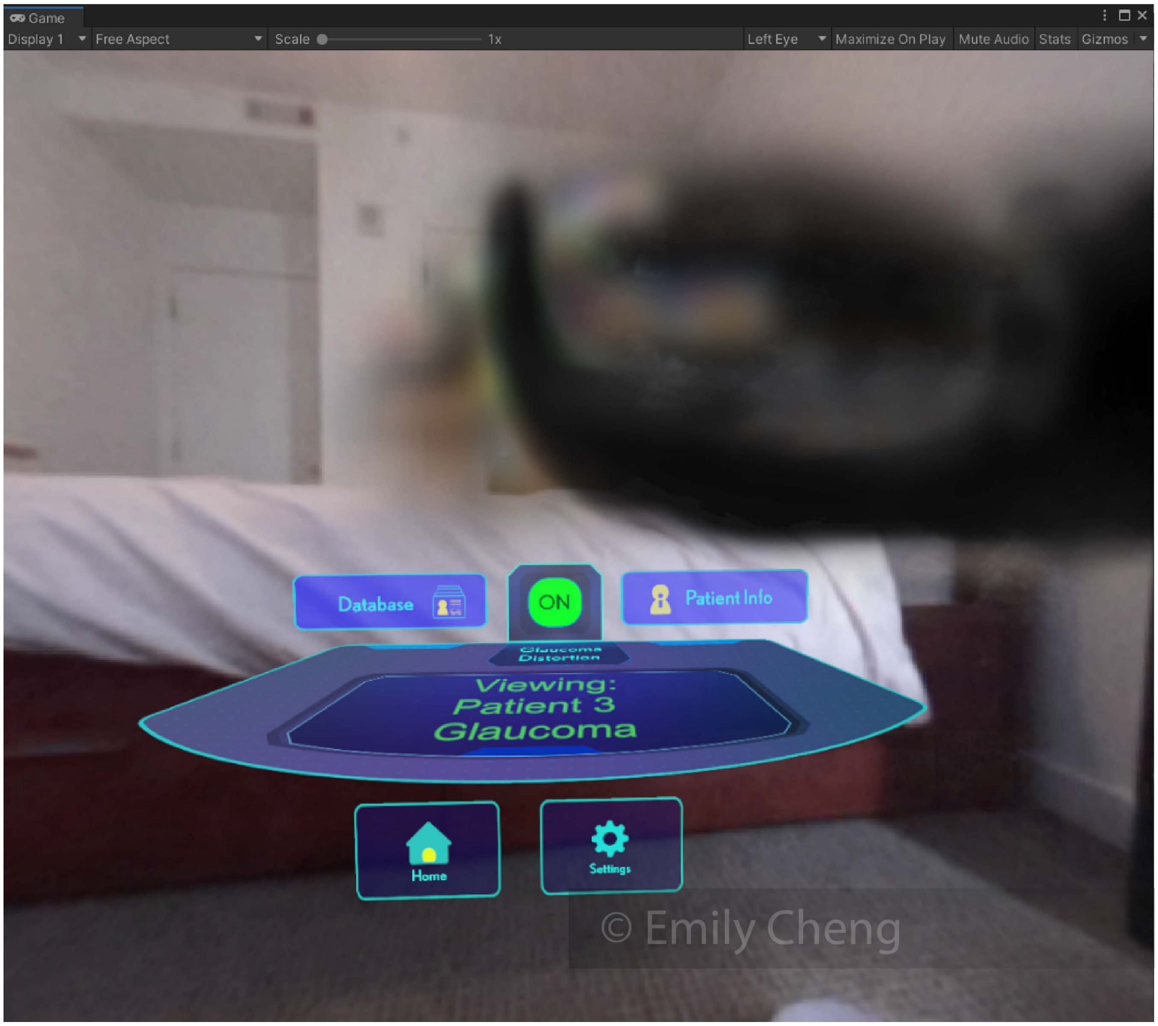


Figure 91. *UI with Only Glaucoma Distortion Toggled On Displaying Patient 03 Distortion. Text not intended to be read.*

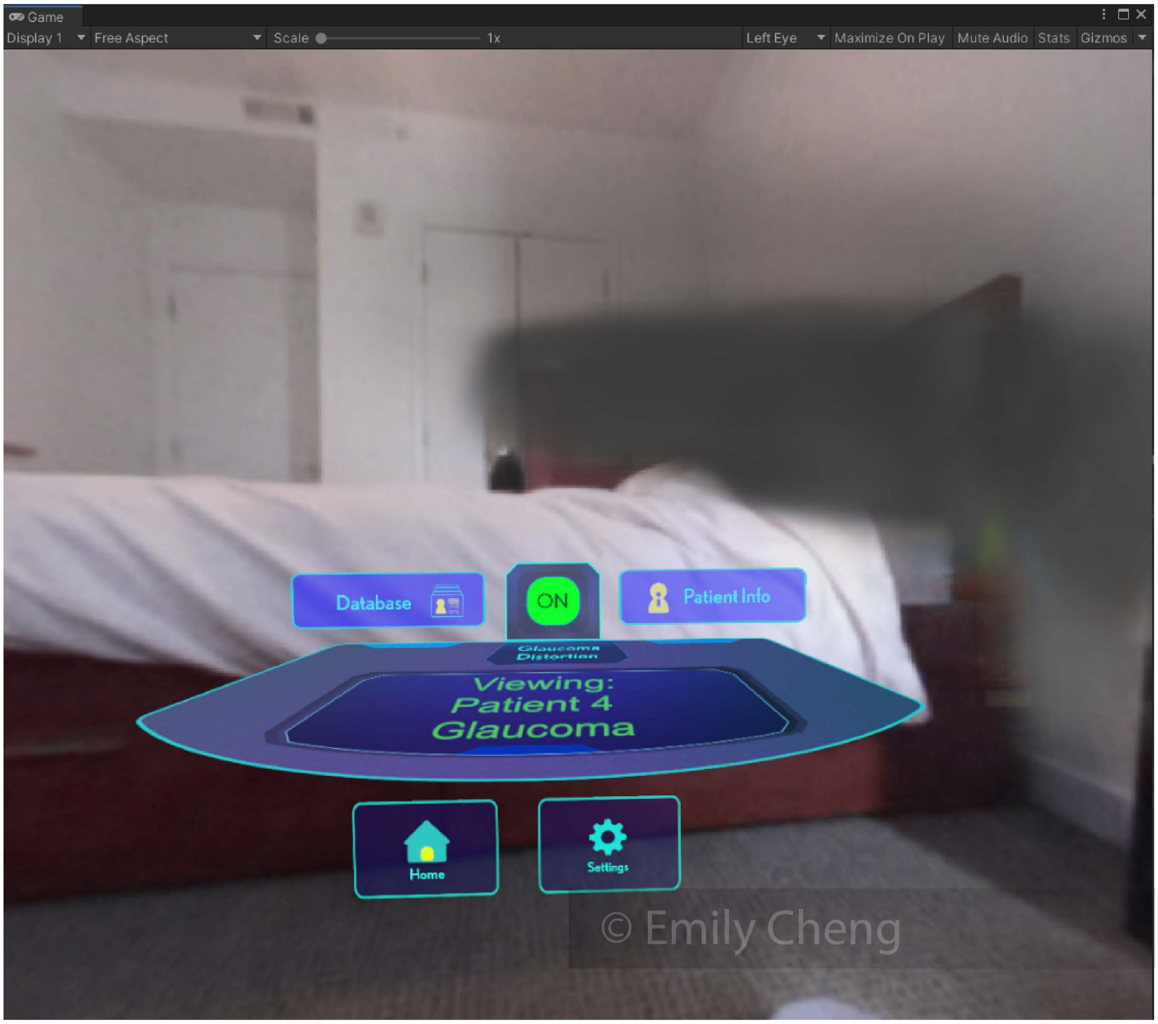


Figure 92. *UI with Only Glaucoma Distortion Toggled On Displaying Patient 04 Distortion. Text not intended to be read.*

Search Task Simulator Module

Search Task Simulator 3D Assets and Final Set Up

Figure 93. *2D Oriented Birds Eye View of Full 3D Modeled Assets in Living Room within Unity 3D.*

Figure 94. *3D Perspective Birds Eye View of Full 3D Modeled Assets in Living Room within Unity 3D.*

Figure 95. *Final Living Room Scene within Unity3D View 1.*

Figure 96. *Final Living Room Scene within Unity3D View 2.*

Figure 97. *Final Living Room Scene within Unity3D View 3.*

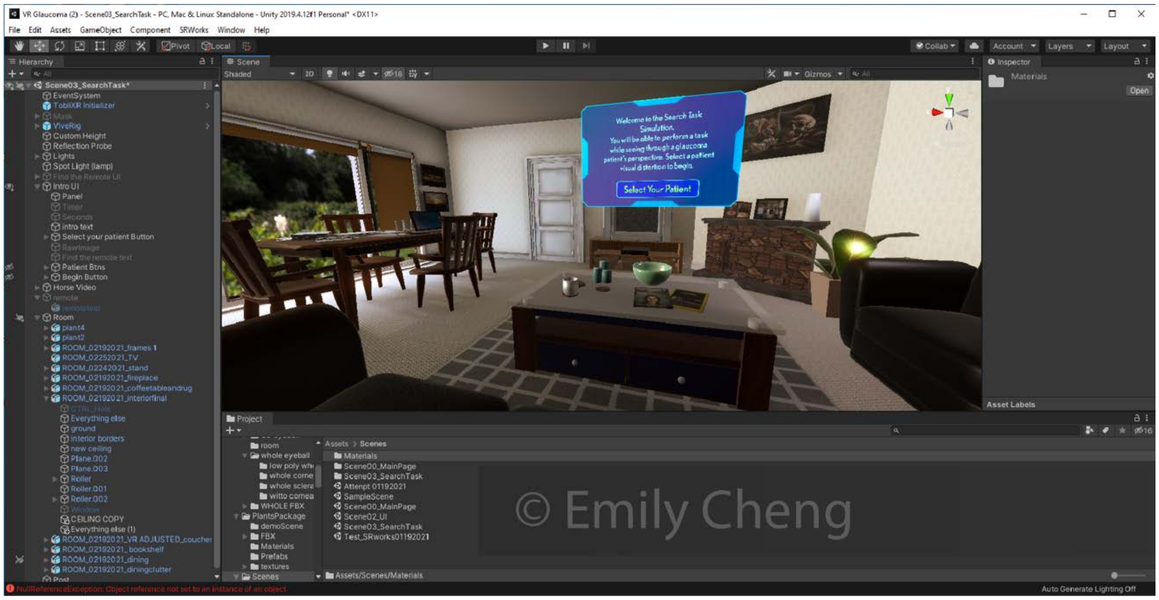


Figure 98. *Living Room Scene within Unity3D interface. Text not intended to be read.*

Figure 99. *Screenshot of Initial Camera View within HTC VIVE Pro Eye.*

Figure 100. *Screenshot of Initial VR View of UI within HTC VIVE Pro Eye. Text not intended to be read.*

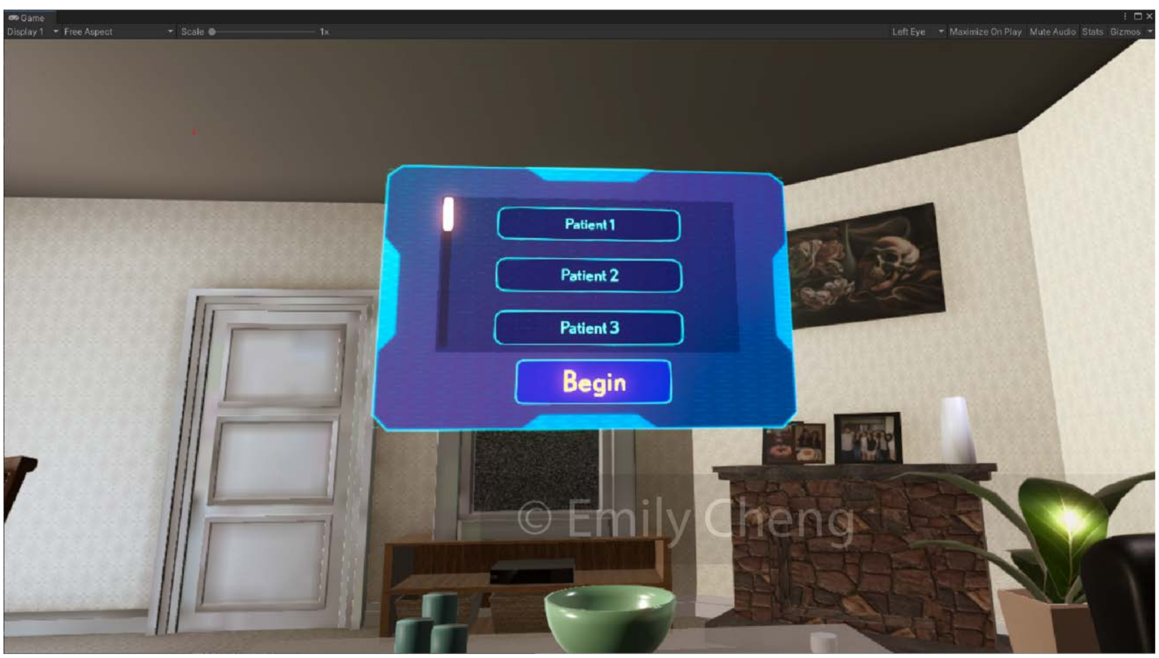


Figure 101. *Screenshot of VR View of Proceeding UI within HTC VIVE Pro Eye. Text not intended to be read.*

A)

B)

C)

D)

Figure 102. *Remote Interactivity with UI (A) Countdown without remote grabbed (B) Successful interaction with remote before timer ends (C) Timer blinking red before reaching 0 without remote grabbed (D) Overtime after having remote grabbed.*

Scene with Imported Patient Glaucoma Masks

Figure 103. *Patient 01 VR View with Imported Glaucoma Mask.*

Figure 104. *Patient 02 VR View with Imported Glaucoma Mask.*

Figure 105. *Patient 03 VR View with Imported Glaucoma Mask.*

Figure 106. *Patient 04 VR View with Imported Glaucoma Mask.*

3D Models and Assets

Figure 107. *Different Views of the Modeled Whole Eye (Left) and its Corresponding Cross-section with Optic Nerve Preserved (Right).*

Figure 108. *Model of Whole Eye (Left) and Corresponding Cross-section with Optic Nerve Preserved (Right).*

Figure 109. *Model of the Eye with Optic Nerve Cross-section.*

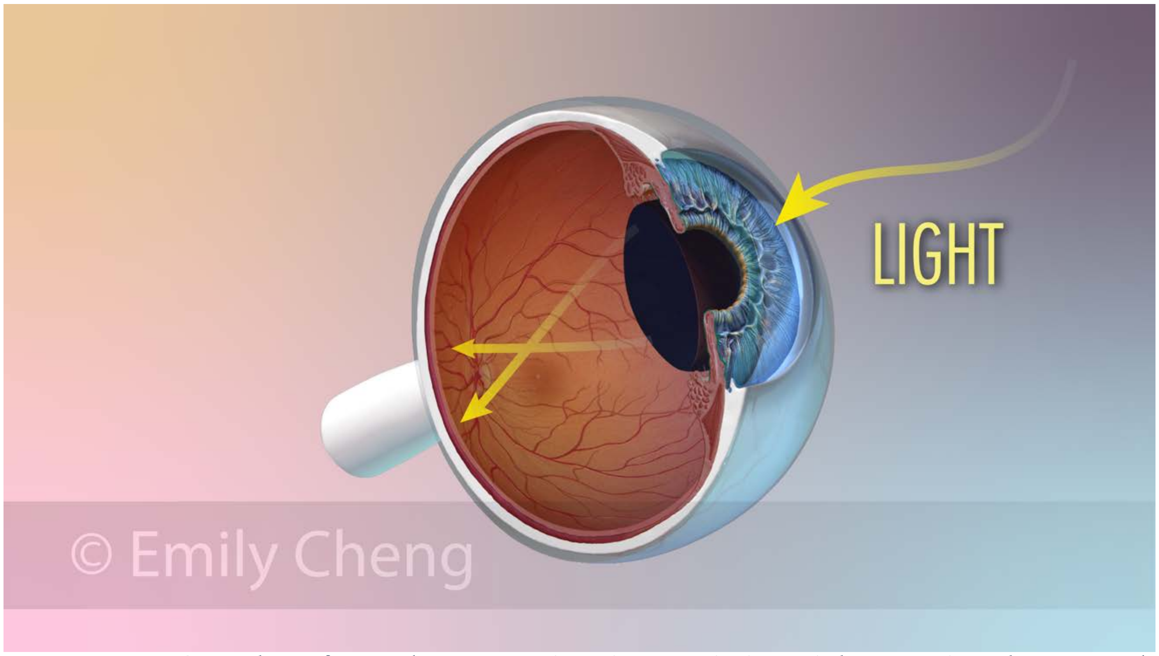


Figure 110. *Snapshot of Introductory Animation Depicting Light Entering the Eye and Hitting the Retina.*

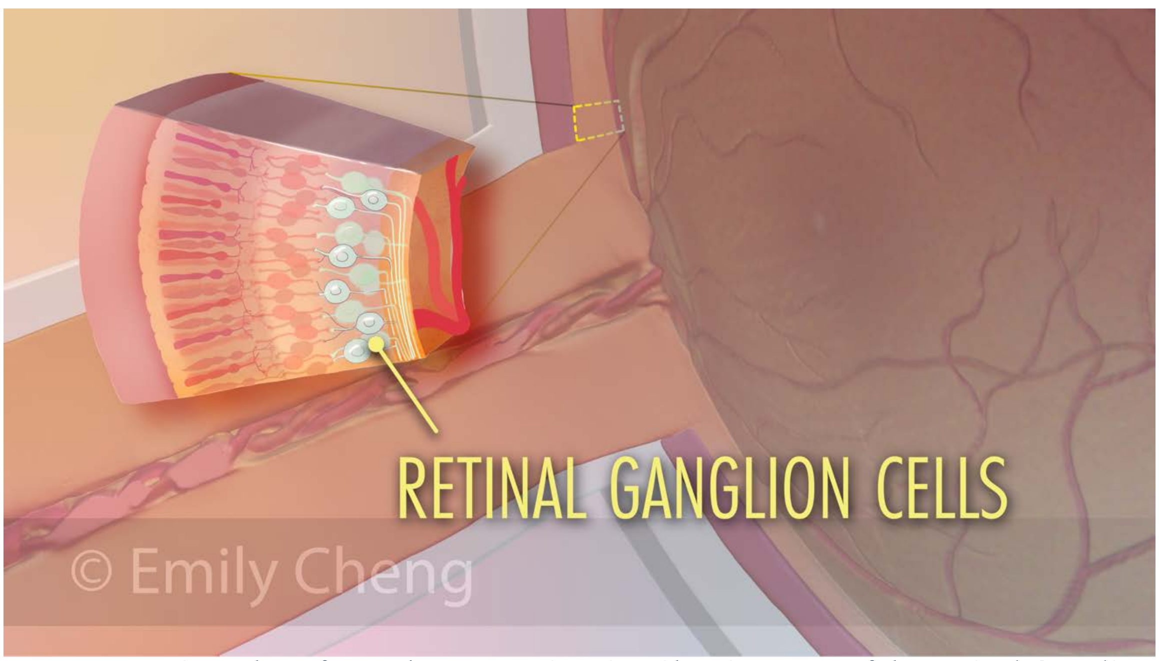


Figure 111. *Snapshot of Introductory Animation Showing Inset of the Retinal Ganglion Cells.*

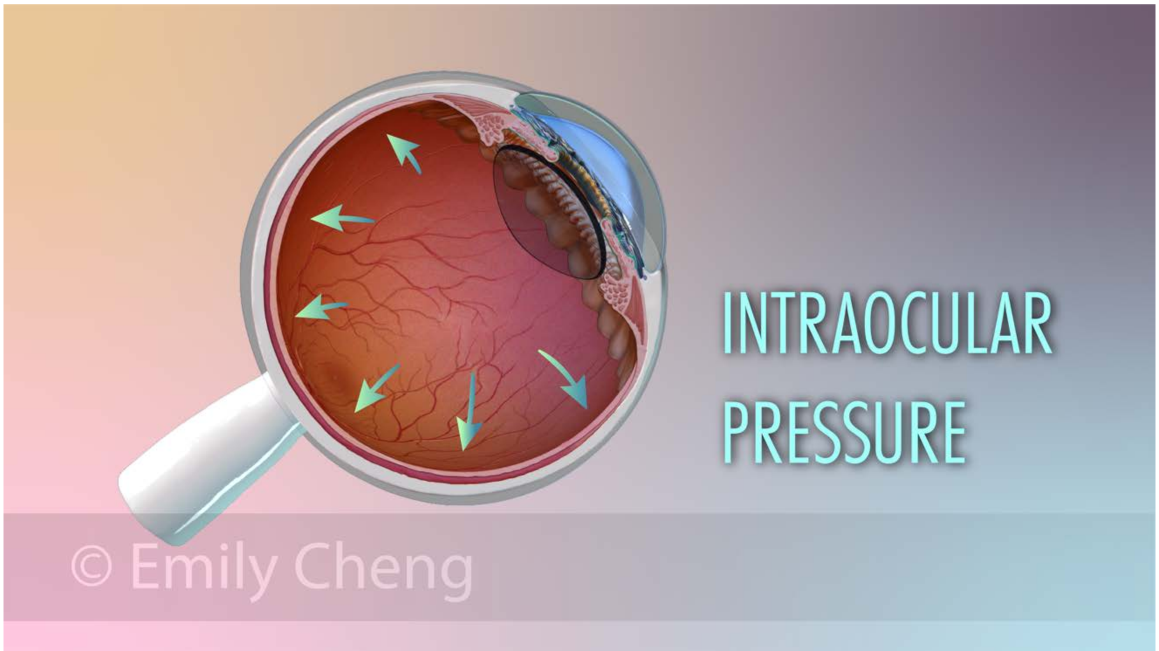


Figure 112. *Snapshot of Introductory Animation Showing Indication of the Rise of Intraocular Pressure.*

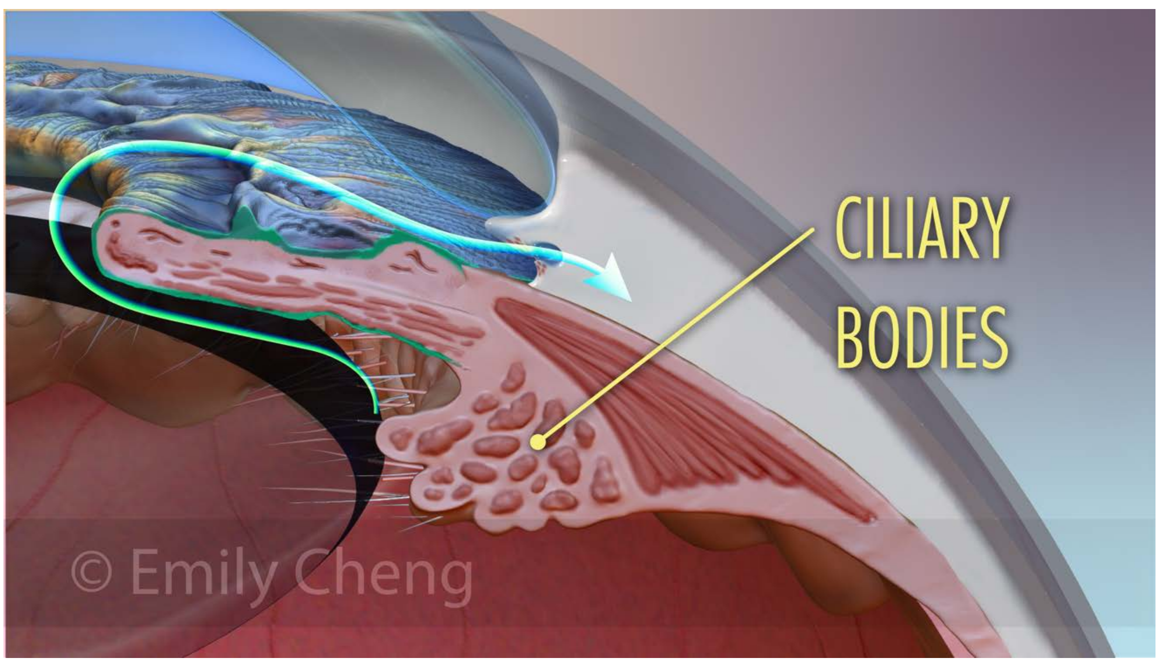


Figure 113. *Snapshot of Introductory Animation with Focus on the Ciliary Bodies and Aqueous Flow.*

Figure 114. *Screenshot of HTC VIVE Pro Eye View of the Patient Module Menu Interface*

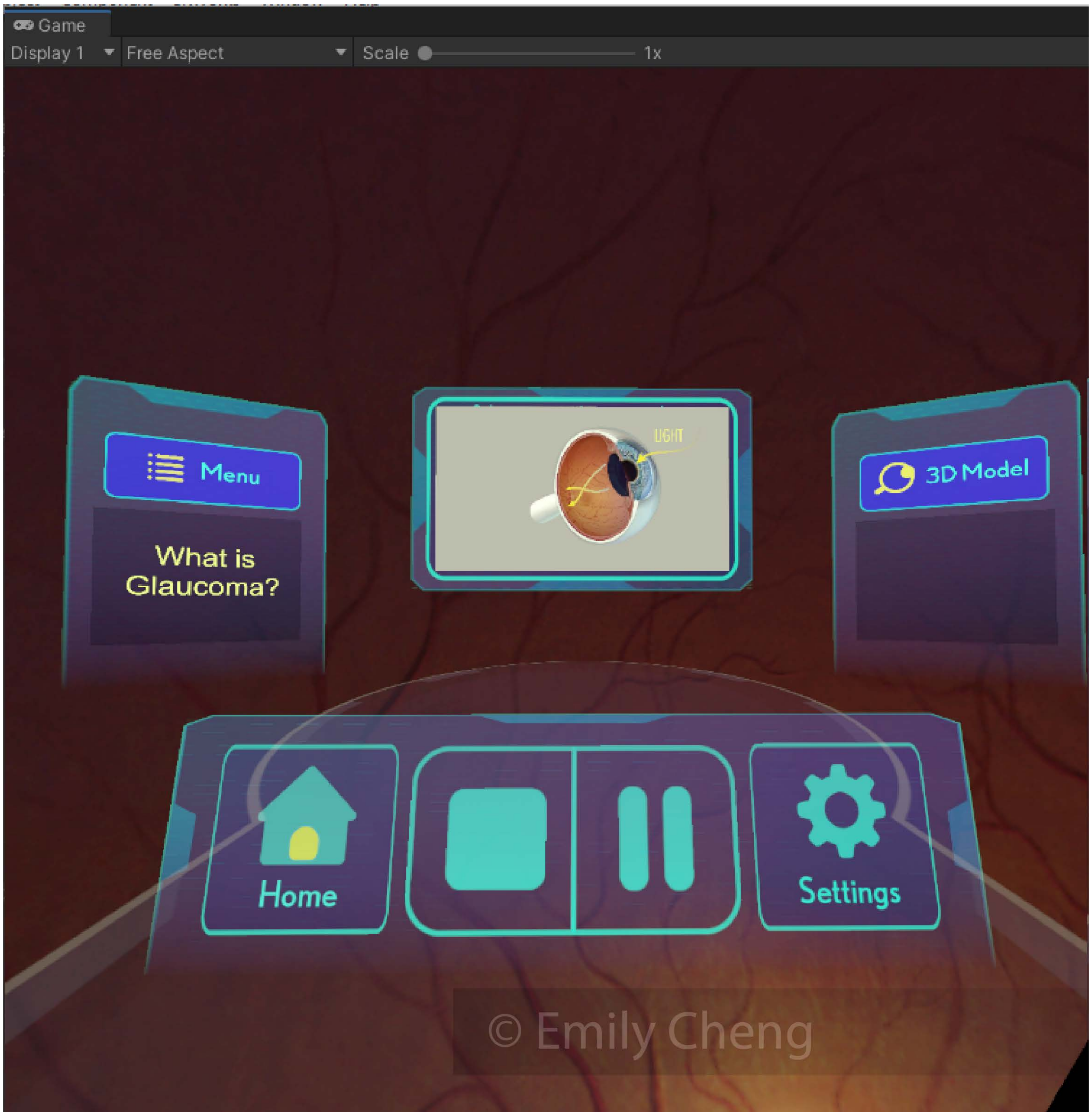


Figure 115. *Screenshot of HTC VIVE Pro Eye View of the Patient Module Animation User Interface. Animation is intended to be playing.*

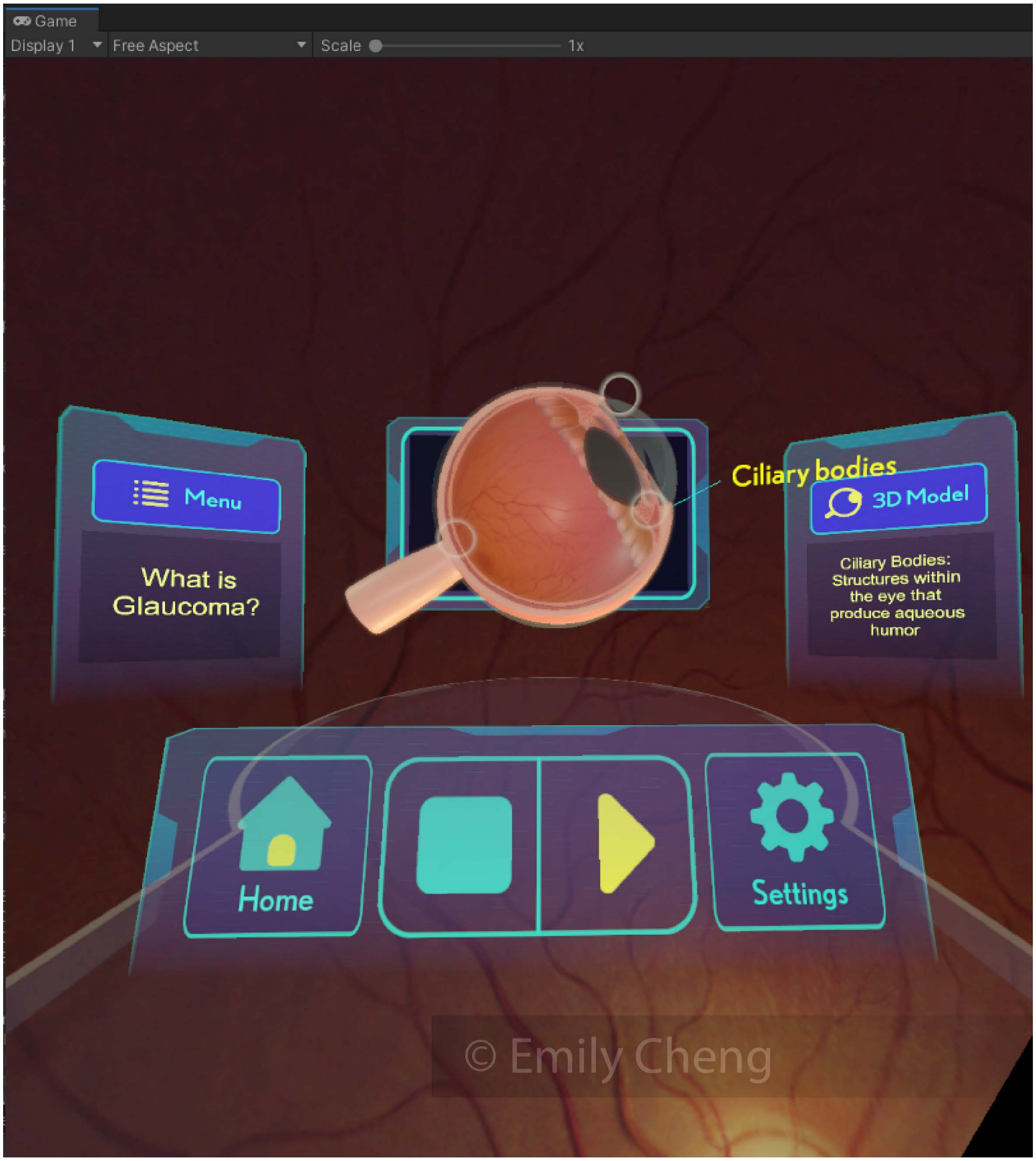


Figure 116. *Screenshot of HTC VIVE Pro Eye View of the Patient Module 3D Model Exploration Interface. Animation in the background is not playing.*

Flowchart/Sitemap

A flowchart was developed in order to establish a navigation plan for the user in the VR simulation. All boxes in light green are executed within this thesis. Boxes with dark green highlights are visible within the interface but have not been programmed to completion.

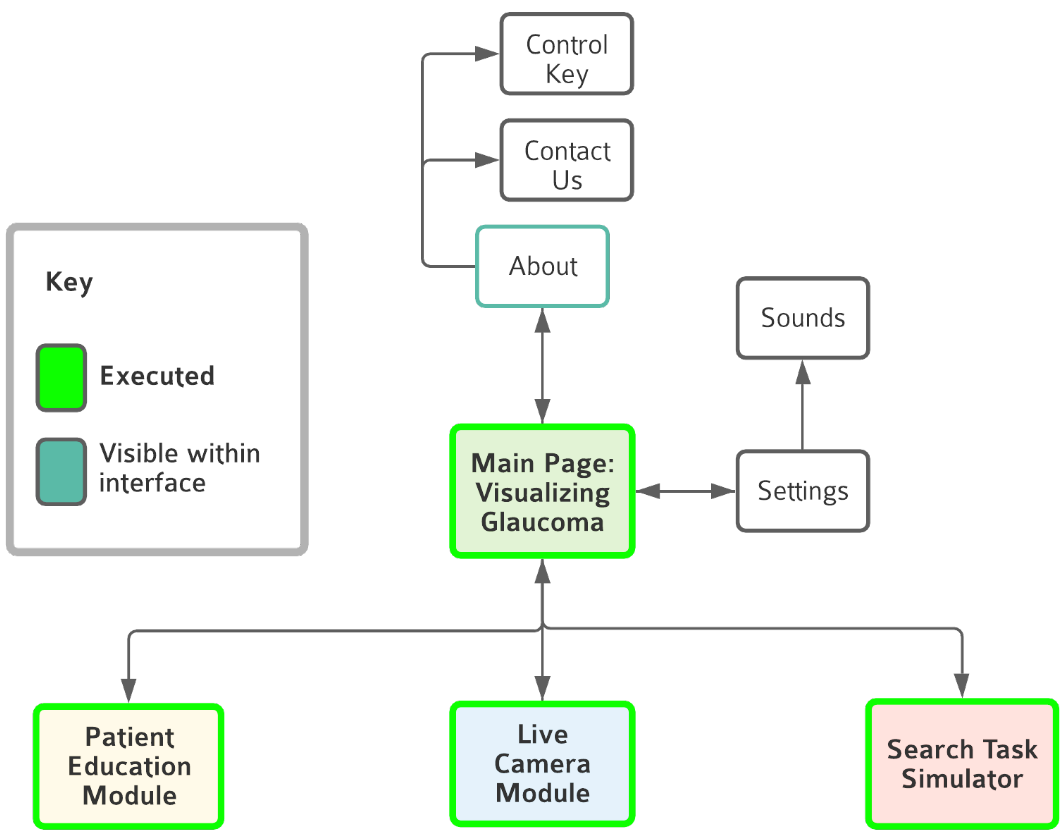


Figure 117A. *Flowchart of Navigation Upon Entering Main Scene. Refer to keycode for highlighted box colors.*

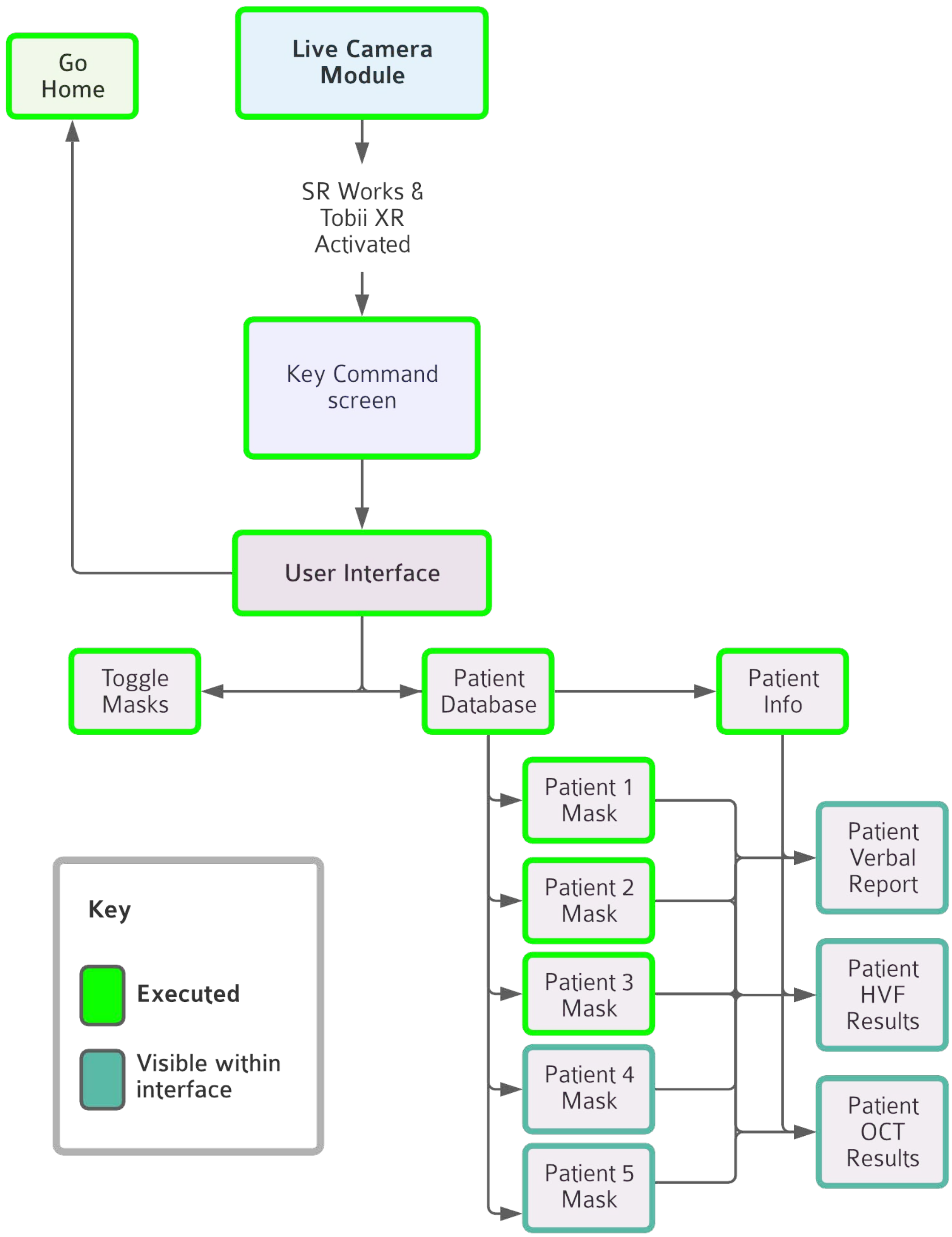


Figure 117B. *Flowchart of Navigation Upon Entering Live Camera Module. Refer to keycode for highlighted box colors.*

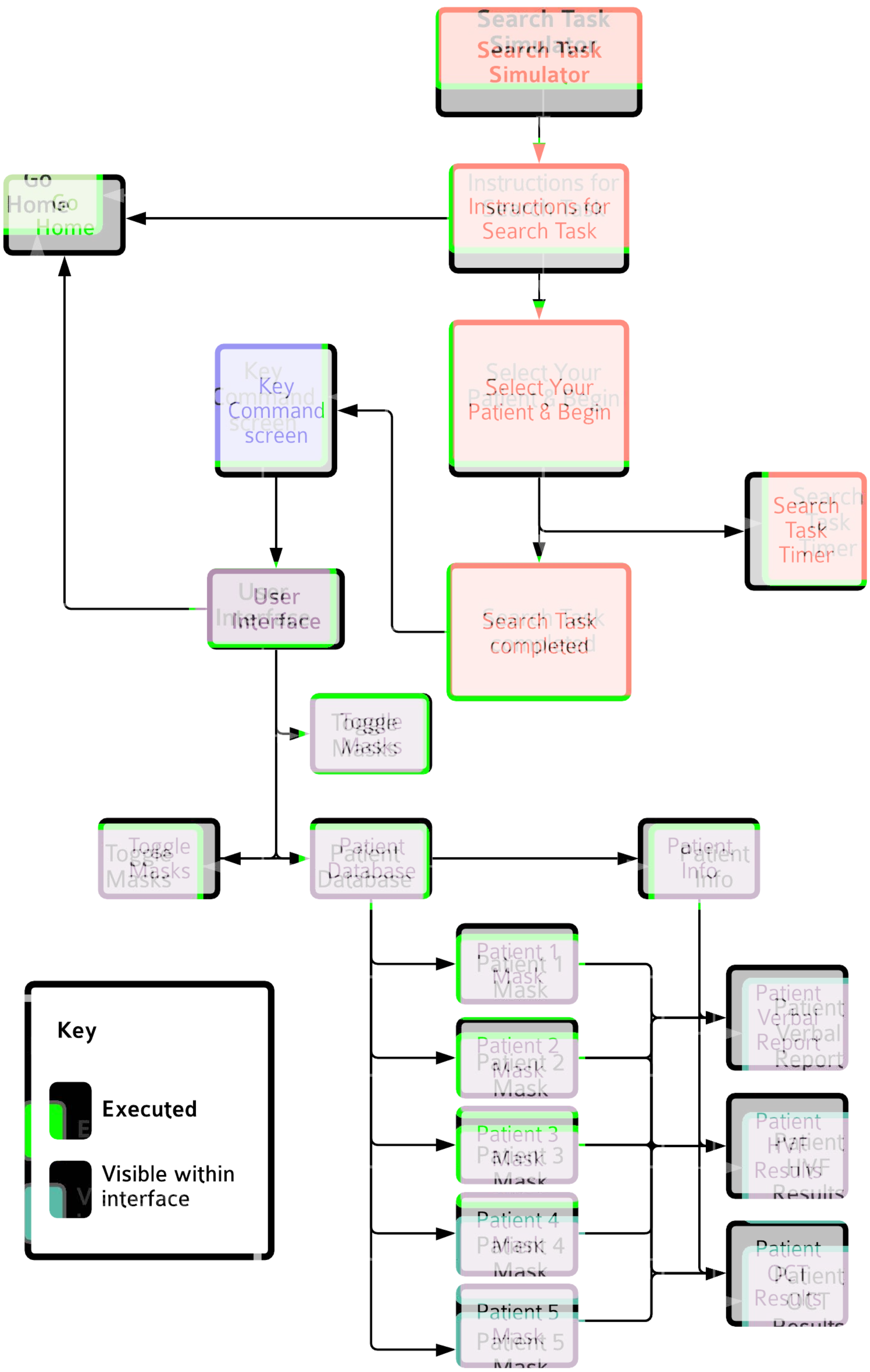


Figure 117C. Flowchart of Navigation Upon Entering Search Task Simulator Module. Refer to keycode for highlighted box colors.

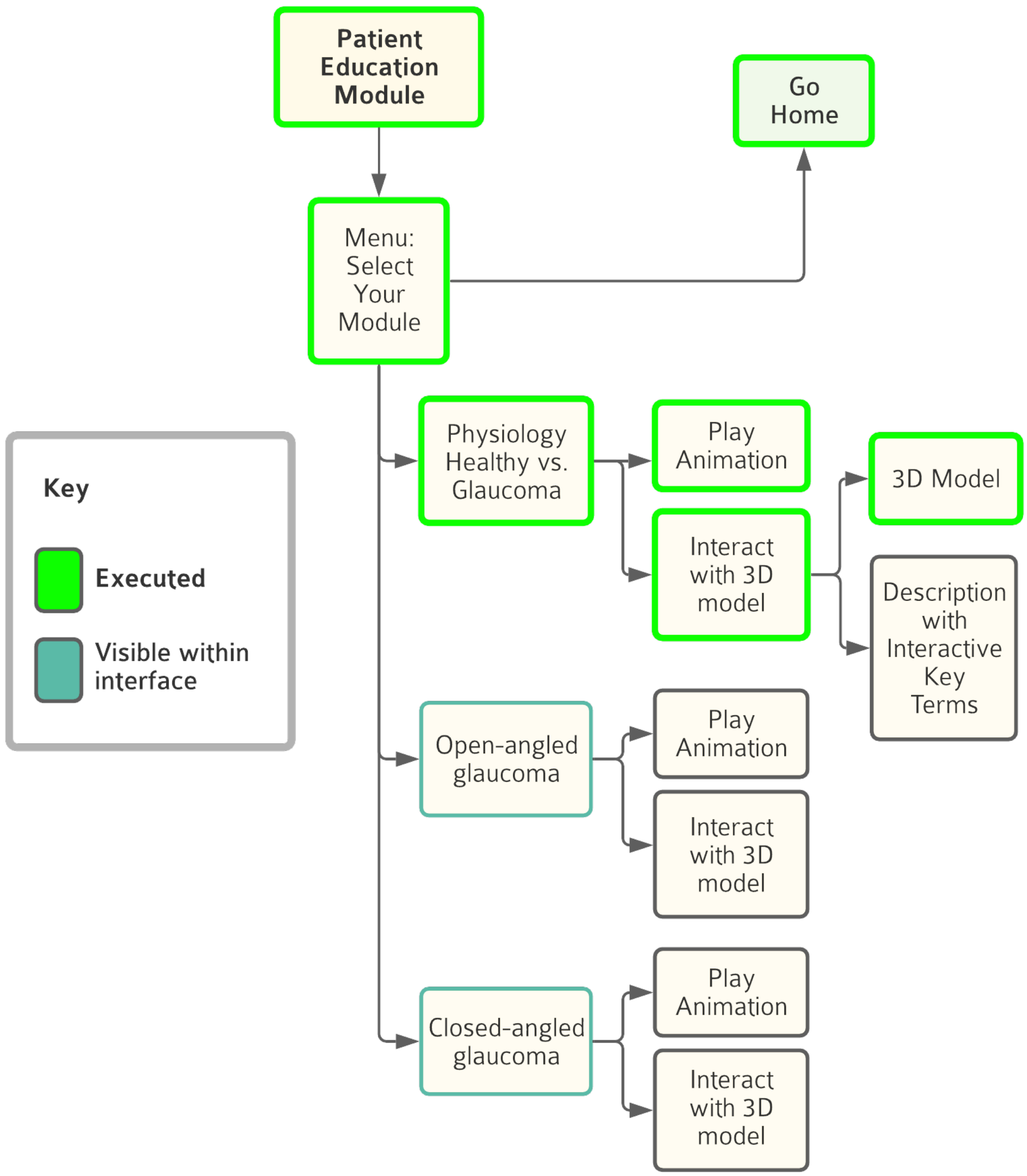


Figure 117D. *Flowchart of Navigation Upon Entering Patient Education Module. Refer to keycode for highlighted box colors.*

Access to Assets from this Thesis

Images of 3D models and demo videos from this thesis can be partially found on www.empiricalmedicalmedia.com.

Access to the models, scripts, simulation may be granted by contacting the author at emiriic@ucla.edu or through the Department of Art as Applied to Medicine at Johns Hopkins University School of Medicine http://medicalart.johnshopkins.edu/.

Discussion

Overview

The development process for this VR application introduced both important decision-making opportunities as well as technical and conceptual challenges that needed to be overcome. Considerations towards COVID-19 also significantly affected the design and our course of research. Our process of conducting this research will be discussed in the following order; (i) the project goals, (ii) hardware and software decisions, (iii) design decisions, (iv) limitations, (v) key innovations relative to existing resources, and finally (vi) implications for future use.

Project Goal

The purpose of this research was to develop and implement a protocol to accurately depict the visual experiences of glaucoma patients and then to simulate that experience in an educationally impactful way within VR, using novel eye-tracking technology. The ability to display a visual view consistent with eye disease in a 3D environment can potentially allow for early-onset patients, family members, and physicians to develop a deeper understanding of the disease, allowing them to be more empathetic towards those inflicted with poor vision. Virtual reality provides a better avenue to deliver novel components of ophthalmic care including elements of care which take into account the patient perspective of their diseases.

The resulting VR simulation should facilitate user understanding of moderate and late-stage glaucoma and the effects they may have on a patient's quality of life. Users should also be able to learn about the importance of vision testing and the forms of data testing provides, as well as structurally relevant eye anatomy and their relation to different types of glaucoma.

HTC VIVE Pro Eye as the Distribution Platform

Currently, there are only a few VR headsets on the market that support eye-tracking technology. These headsets have a wide range of price points. Within this selection, VIVE Enterprise has been on the frontlines of producing competitive VR headsets and was one of the first to integrate precision eye tracking and foveated rendering in their product. Their headset, the HTC VIVE Pro Eye, has a high resolution 2880x1600 OLED display that is sold at a more affordable price than other eye-tracking competitors (see Table 5). It has a pixel density of 615 PPI, and a field of view (FOV) of 110 degrees which makes it a valuable choice for building an application that focuses on visual defects. The front-facing camera within the VIVE Pro Eye also provides the opportunity for an immersive augmented reality (AR) experience.

Two eye-tracking leading competitors are the Varjo VR-3, and Pico Neo 2 Eye. While the Varjo VR-3 contains strong performance power, it is triple the price, heavier, and only compatible with SteamVR. The Pico Neo 2 Eye, released just earlier this year, has lower refresh rate and does not contain passthrough cameras or sensory haptics in their controllers. Furthermore, its lower quality software could end up making visuals look underwhelming. These headsets were also not currently available for retail use at the time of this publication, extremely new to the market, and lack the track record HTC VIVE Pro Eye has established in market.

	HTC VIVE Pro Eye	**Pico Neo 2 Eye**	**Varjo VR-3**
Display Resolution (per eye)	1440 x 1600	1920 x 2160	1440 x 1600
FOV (degrees)	110	101	115
Pixel Density (PPI)	615	818	3000
Refresh Rate	90 Hz	75 Hz	90 Hz
Weight	550 g (with headstrap)	690g (with headstrap)	944g (with headstrap)
Price	$1599 (headset, controllers, base stations)	$899 (headset and controllers)	$5495 (headset only)
Controller	2 x HTC VIVE controllers Haptic thumb and index finger tracking	2 x Pico Neo 2 Controller	N/A
Front-facing camera Resolution	Fisheye 640x480	2 x mono fisheye camera (resolution N/A)	N/A
Compatible platforms	SteamVR, Viveport	Viveport	SteamVR

Table 4. *Comparison of HTC VIVE Pro Eye, Pico Neo 2 Eye, Varjo VR V-3.*

Technical complications

Setting up the HTC VIVE Pro Eye was a complicated process. There were several compatibility issues between the Pro Eye and the MSI gaming laptop used to run Unity. The first issue was an incompatibility of the display port (DP) cable provided by HTC which was meant to be inserted into a regular display port, while the MSI gaming laptop only had a slot for a mini-display port. To address this, a DP to mini-DP adapter was purchased. However, despite the system detecting the headset, the headset itself eventually would not turn on at all. Further troubleshooting prompted an update for laptop BIOS file, in addition to a software update which resolved most of the issues. Future approaches to using a VR headset should involve screening for device compatibility and ensuring all device drivers are up to date.

Application of the HTC VIVE Pro Eye Forward-Facing Camera

The goal of utilizing the forward-facing camera on the VR headset was to allow the user to be able to directly compare vision degraded by glaucoma to their own vision. This may allow for the user to notice the changes that accompany glaucoma damage and understand how the vision would be like at moderate to late stages of the disease. Having eye-tracking and foveated rendering performed in an augmented environment is also new technology that opens possibilities to further increase the realism of simulated glaucoma. There are, however, a few limitations with the use of this camera that will be discussed in detail in the limitations section.

Unity and C# Scripting

Unity is a game engine platform of choice as it boasts a robust library of virtual reality plug-ins and toolkits, as well as strong 3D capabilities that make it a versatile and standout choice for VR game development compared to other game engines.

While Unity can read other programming languages, it inherently programs using C#. As C# is Unity's native programming language, it was selected over Javascript. C# is a more straightforward program to pick up compared to other existing languages, such as C++ and Python. It is an accessible language to the public. Code for other game engines typically use C++, which suffers from a steeper learning curve.

Unity also contains a vast and thorough online manual with all of its published application programming interface (API), or the library of terminology that can be used to execute functions within the C# code. Having easy access to the API allows for more straightforward scripting and access to information when needed.

Unity Universal Render Pipeline

The Unity Universal Render Pipeline (URP) was selected over the Built-in Pipeline as it is a pared down version of the built-in pipeline that streamlines memory performance while also including several plug-ins and packages that is intended for optimized VR use. URP is compatible with numerous major game platforms and provides high end performance with beautiful graphics. Its physically based lighting and materials and single-pass forward rendering allow for high quality renders with optimized computer memory use.

Use of Blender and ZBrush

ZBrush is the current standard for 3D digital sculpting and offers a diverse range of tools that handles a monumental amount of geometry while still maintaining performance. Its available material bank as well as BPR render tools provide an easy and fast workflow that produces a complex, finished product within one program.

Blender is a free 3D modeling tool that is more versatile and less specialized, and is advantageous to use due to its affordability and cross-platform compatibility. Unity also natively imports .blend files, which make meshes, materials, and texture map assets easily transferable. Its interface has a versatile geometry-building tool kit that is well suited for interior design work and architectural based asset modeling in addition to handling more complex and fluid modeling.

Patient Visual Assessment Tool Set Up

Many considerations were made in developing the patient visual assessment tool. A major decision was to present the images in a two-dimensional set up. Two major reasons influenced this decision. First, it was imperative to minimize risk of COVID-19 transmission, by projecting the2D images on a screen using remote teleconference software like Zoom. Easily controlled clinic visits was an effective way to comply with that. Second, having the tool administered in 2D format allowed for live-editing to be made during interview sessions on Adobe Photoshop CC 2021.

Initially, we structured the tool to first regionalize the affected areas by dividing the space into 4 quadrants. Next, we filled in these areas with distortions live, solely based on patient feedback. This brought up concerns of time allocation for this task. While starting from a blank slate allowed for flexibility, deciphering the patient specific pattern of impairment from scratch could risk having the patient interview session extend far past the amount of time (~2 hours) that could be reasonably allocated for the task. Instead, we decided to present the test subjects with distortions in the full field of view, and then localize the distortions to the areas where they report experiencing those distortions. The latter method was believed to be more effective than the former as it does not rely on the patient to entirely conceive the image and rather introduces a modifiable baseline that the patient can more easily compare and contrast.

Photoshop was the program of choice as it allowed for flexible construction of 2D patient specific visual assessments, including the development of prepared distortions and filters. Elected distortions that were prepared for the visual assessment represent distortions that were shown to be present in patients with varying levels of visual field (VF) damage. Namely, these distortions included peripheral vision loss, missing patches of vision, and cloudiness – significant visual defects described by patients who had varying levels of glaucoma severity (Ramulu 2020). Initially presenting these prepared distortions can create opportunities for patients to compare those distortions to their own visual experience. Subsequent manipulation of the distortion image mask can be executed more thoroughly and simply.

Thought was also placed into selection of the grocery aisle scene that was presented within the visual assessment tool. Primarily, the visual complexity of the scene would capture all quadrants of vision so that the clutter allows the patient to finely distinguish subtle variations of visual distortions with relation to the image content. Thus, things that may be “missing” or difficult to see will be more apparent and more effectively addressed.

Several considerations were also implemented in designing the look and procedural protocol for the cursor and points of focus during the visual assessment. The objective was to develop an easy method to indicate the area of discussion in order to minimize confusion. This means the cursor needed to be extremely bold and visible, resulting in selecting a saturated red color for it. A color-blind filter was placed on the overall assessment image to make sure that there was adequate contrast and visibility for colorblind patients (Figure 118).

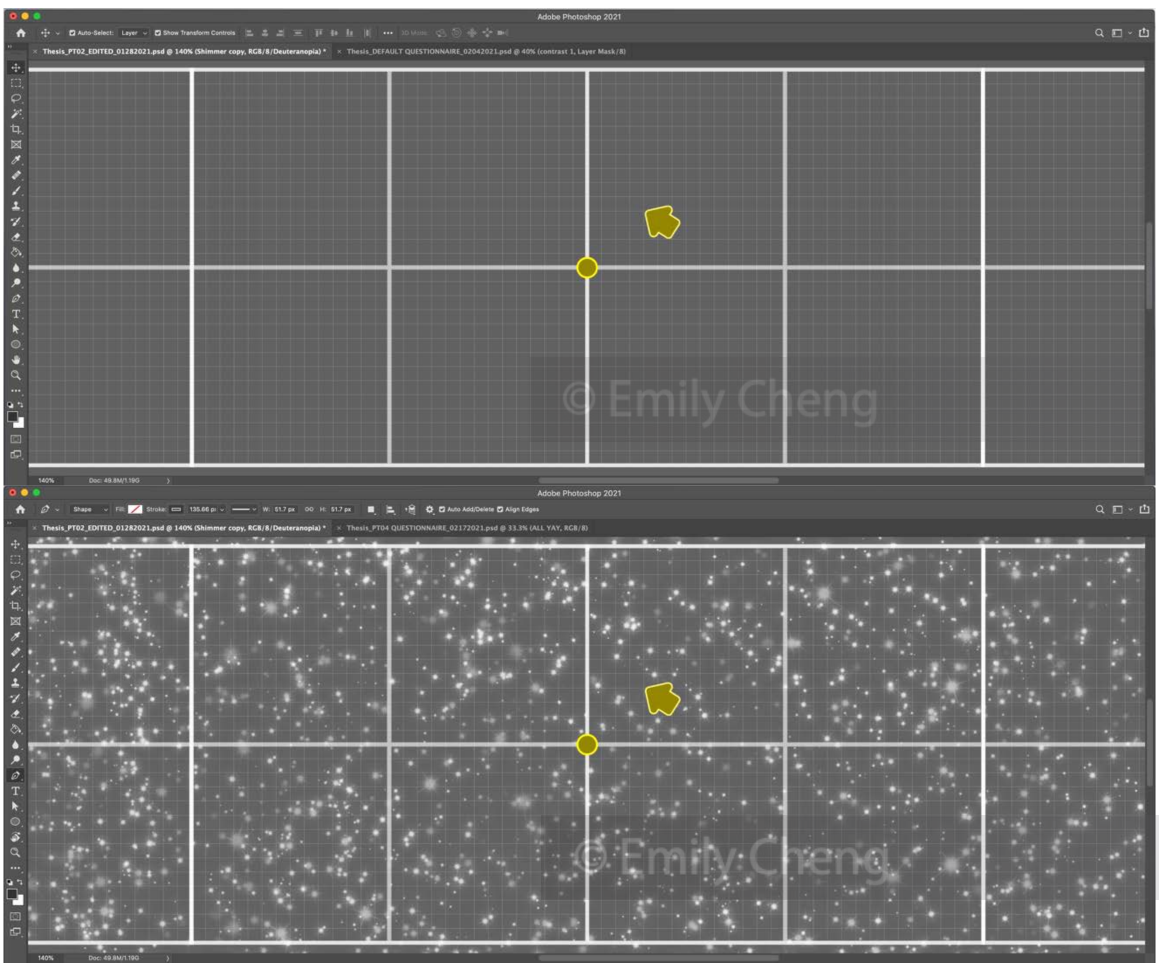


Figure 118. Screenshots of Color-blind Mode of Default Assessment Grid and Shimmer Mode. Text not intended to be read.

Like many visual exams, the cursor acted as a point of fixation during their assessment, allowing the viewer to gage distortions without having their point of fixation constantly move. The focal point thus also needed to be easily discernable to easily draw the viewer and ensure that the distortions captured are regionally accurate without occupying too much space. It was therefore assigned the same saturated red color. The colors for the cursor and focal point were kept consistent so patients did not have to register extra information while participating in the assessment.

The cursor was moved in small circular motions during the administration of the assessment to extract information on whether the patient could register movement where the cursor was, even if they could not register colors or shapes. This helped better distinguish how much vision loss the patient was experiencing and what kind of information they were still able to perceive. The focal point was moved around to assess a wider range of peripheral vision, which can then be added into the final composition of distortion.

To determine the best distance patients should sit from the monitor space, the initial angle of peripheral view was first identified. Since the standard HVF test typically assess vision within 30 degrees of fixation, and 60 degrees from the point of fixation is determined to be the upper end of the mid peripheral measure, we determined 70 degrees from fixation to be a generous enough peripheral range to depict within a VR setting. Additionally, considering that the HTC VIVE Pro Eye headset itself has 110 degree field of view, having 70 degrees from the point of fixation in both eyes will allow for some lenience of the amount of peripheral distortion being captured.

Subsequent sessions with the patient were conducted remotely to minimize risk of COVID-19 transmission and to reduce patient trips to the clinic. This introduced some limitations with the types of information that could be verified during these sessions which will be discussed later in the limitations section.

Ideally, in a non-COVID setting, patients would have access to the VR station to experience the simulated condition and to verify its accuracy. However, because of the current pandemic, allowing different patients and personnel contact with the same VR headset would increase transmission risk for COVID-19. Therefore, this was decided against in the overall patient interview protocol. This does not detract from future instances where the pandemic will no longer be a factor and studies can resume with less risk.

Use of GazeVisualizer in Unity3D

Importing the developed patient specific visual distortion masks into Unity3D also involved novel implementation of the GazeVisualizer from TobiiXR. Using the Spriterenderer in conjunction with the GazeVisualizer was the most straightforward method of attaching visuals to eye tracking that didn't involve extensive manipulation of C# and still utilized all of the eye tracking data from TobiiXR. The Spriterenderer function allows ability to select a specific sprite of choice (representing a patient specific visual distortion mask), which was specifically useful for applying the various image masks.

The size and distance of the rendered sprite could also be modified through this method. Some troubleshooting was done in order to import the image masks at their desired original dimensions. Initially, with the original GazeVisualizer script, the image masks were rendered at an extremely small size in "Play" mode. After testing several settings, it was determined that if the "OffsetfromFarClipPlane" was set at a small distance, the image mask rendered smaller, and when set at a large distance, the image mask scaled upwards. This prompted examination of the GazeVisualizer script, in which it was discovered that the size of the rendered sprite was being multiplied by its distance from the camera clipping plane. The line of code dictating this was subsequently adjusted.

UI Menu Design

The objective of the theme for the user interface is to increase incentive for user engagement. The visual aesthetics served to entice the user into learning about the important educational materials presented within the application. A futuristic theme was applied to reflect the modern concept of using VR technology to depict a healthcare condition. The color palette also ranges in hues of purple and yellow, which is highly compatible for color-blindness. (Figure 119).

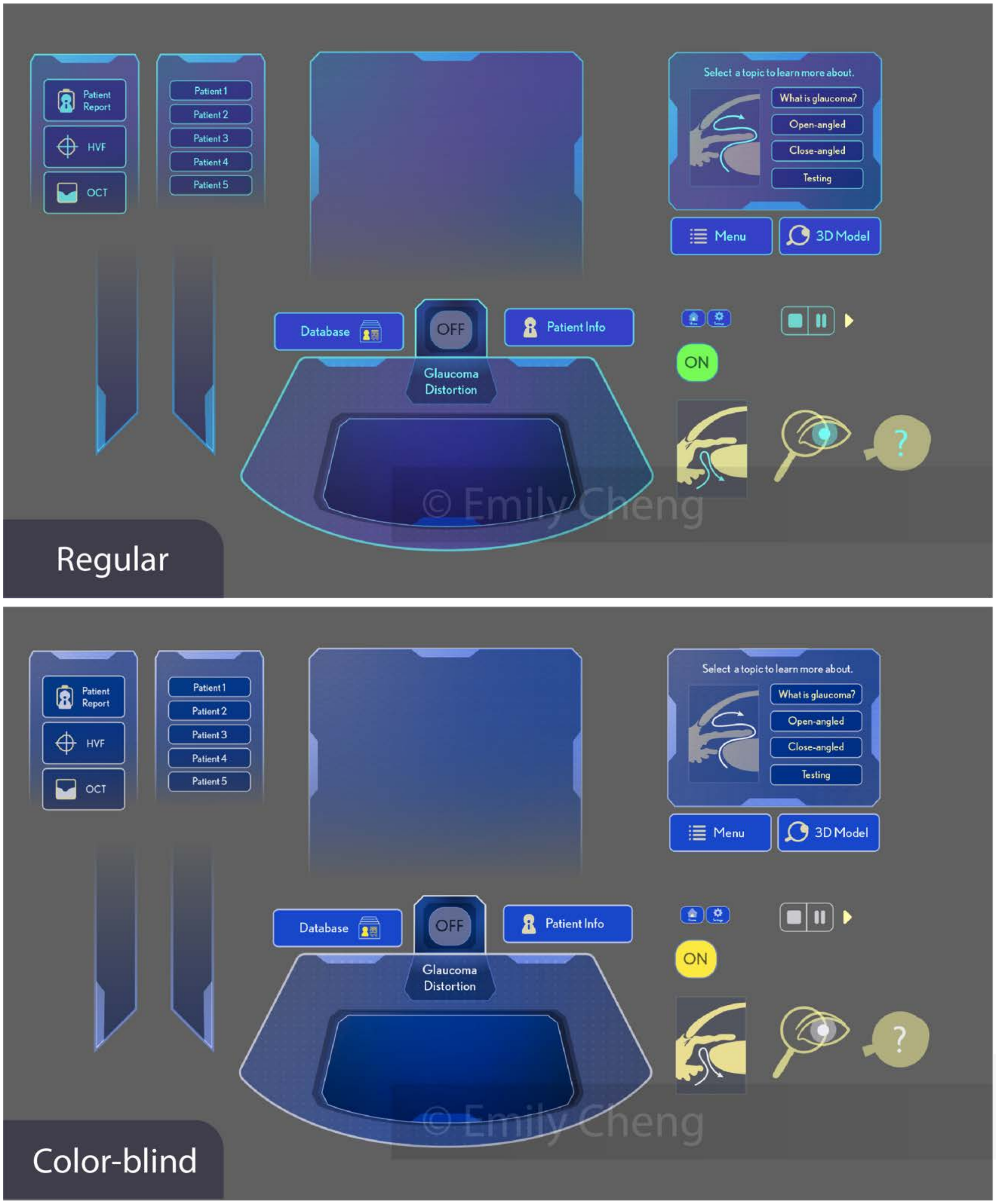


Figure 119. *Interface Compared in Color-blind Mode Depicting Clarity of Contrast. Text not intended to be read.*

Each type of user interface is designed with specific goals in mind:

Main Scene

The environment places the user in a perspective they would not be able to see in the real world, and while it serves to interest the user, it could also provide a partially educational or informative point of view. Each module is encapsulated within an orb like object. The idea behind this is to allow the user to feel as if they have the ability to physically interact with an energy that they may not be able to experience in the real world. This aims to provide the user with a sense of immersion and encourage excitement with using the app.

Search Task Simulator/Live-Camera

The user interface placed within the Search Task Simulator and Live-Camera Modules was designed to give users the feeling as if they are using a control panel. The interface itself was made slightly transparent in order to have it blend more naturally into the environment. To increase visual contrast, the palette was made dark with bold highlights.

The different UI elements were placed 2 – 3 Unity units away so that it would be a comfortable distance away to use the Raycaster interface smoothly for feature selection. The information board is also sized at 2800x1730 pixels, so that text and images are legible, especially for a potentially visually impaired older user.

Patient Education Module

For the patient education module, the user interface takes on a simpler design so that the focus remains on the larger canvas used to play the educational animations. The canvas was given 2880 x 1730 pixel dimensions, making it slightly over 1.5x size the length and width of 1920 x 1080 HDTV resolution, to accommodate for a comfortable viewing experience while playing animations.

Two important features within this interface are the "Menu" and "3D Model" buttons. The buttons are therefore given bolder, brighter colors for emphasis. The interface was kept within the main scene to minimize unnecessary introduction of new visual elements. The user would thus not have to reorient themselves after being placed into a new environment.

The 3D model feature was implemented to offer the user a chance to further engage with the structure presented within the animation. It also allows the user to be able to view some of the anatomical structures introduced in the animations from a perspective that may facilitate their understanding and learning. Labels on the 3D model move with the model in 3D space to keep the viewer oriented and allow for more straightforward understanding of material.

User Interface Future Design Directions

It is anticipated that the design of the user interface will continue to evolve based on better user feedback, continued conceptualization, and addition of new features. The design decisions made in the current rendition will referenced or adopted and will contribute to the continued progression and improvement of the VR application.

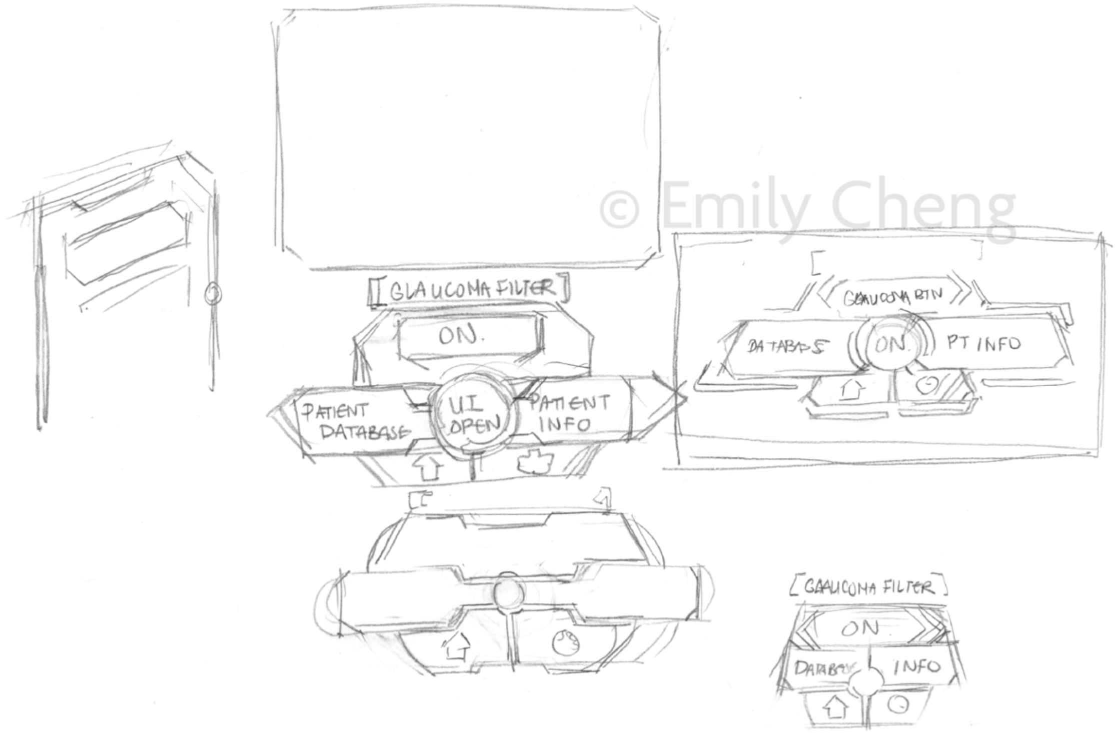


Figure 120. *Continued Conceptual Rough Sketch Designs for Future UI Upgrades.*

Selection of Topics for Patient Education

Several considerations made in selecting topics for patient education revolved around prioritizing what was important for patients and secondary lay audience members to understand about what causes glaucoma. This included an introduction on how regular vision works, what causes glaucoma, different types of glaucoma, and what kind of information specific visual exams test for in this disease. Relevant anatomy is introduced with each of these topics to provide the user with an understanding of the specific parts of the eye that are affected and result in their condition as well as the degradation of vision. All of these topics are considered to be fundamental concepts that can help the user become informed about the reasons behind their vision loss.

Use of Animations

Animations are an efficient way to control the narrative and properly distill important information for the user to absorb. Among the short animations brainstormed for teaching within the patient module, the introductory animation was prototyped as a representative sample of the level of educational information considered appropriate for the module.

The animation remained on a simple background, so as to not detract from the main educational focus of the 3D model and insets. Different angles and cross-sections were used to discuss important anatomical elements physiologically involved in the development of glaucoma. When discussing light entry and the optic nerve, the optic nerve was kept intact to provide a full perspective of the structure being discussed. After establishing its position in the back of the eye, the optic nerve was cross sectioned and zoomed in on to introduce the specific retinal cells that pass through it. The cross-sectioned view also allows revealing the pathway of signal transmission.

Arrows were added during post process using Adobe After Effects CC 2021 in order to add visual reinforcement to some of the concepts being narrated within the animation. The 2D feel of the graphic elements are meant to contrast the 3D structures to easily reinforce the teaching content. Similarly, the inset is rendered in Photoshop CC 2021 as a 2D asset to provide the visual contrast needed to highlight the anatomical structures of importance.

Future renditions could involve producing 3D animations that can be viewed in 3D space as opposed to a projected 2D screen within the 3D space. This could potentially introduce another level of engagement and interaction for the user and allow for more ways for the user to absorb information. Anatomical structures introduced in the animation could then also be viewed relative to surrounding structures at multiple angles.

Simulator Space Design

A living room space was chosen as the environment for this activity as it is a common space for older people to relax and watch TV. Therefore, attention and effort were made to modeling what resembles an older TV model. The living room is designed to look “settled in”, with some added clutter. The user thus is viewing the space from the perspective of a patient who has been living there for some time.

Depicting Clutter

Clutter is a detail that was added within the simulated scene to increase the difficulty of finding a small object like a TV remote. Visual clutter would serve as a distractor from the object of interest. This serves as a teaching opportunity to portray how the disease can impact a visually impaired patient faced with having to process an overwhelming amount of visual information as they are looking for something.

While application of detailed textures provided a moderate amount of the clutter, creating a multitude of varying types of 3D objects is what could ultimately portray an even more effective scene. The amount of clutter could have been increased to reflect an even greater amount of visual distraction. Future development could include more 3D modeled household items to make the environment even more effective at distracting the eye from finding the remote.

Consistency of Lighting Across Assessment and Virtual Spaces

The lighting within the simulated virtual scene is constructed to reflect daylight temperature indoor lighting, which is consistent with the arrangement of the lighting used during the patient interviews. Lighting itself was not a data point that was accounted for during the patient interviews. Nevertheless, it was decided to make the virtual environment at least similar to the typical conditions of the interview environment.

Efficient Use of Texture Maps within Search Task Simulator Module

In order to effectively produce a convincing search task scene, the environment needed to be as realistic and believable as possible without compromising performance within the headset render engine. Normal and displacement maps were useful in conveying the illusion of depth and realism without increasing processing requirements.

The use of render-intensive assets was limited to large furniture and walls in order to display just enough detail for the scene to be believable. The remaining, smaller household items were wrapped with one material that contained multiple textures. Supplementary maps were not needed for these items as they were meant to sit in the background with minimal interaction. The look and general presence of the object is enough to achieve the desired realism without costing rendering time and slowing down the simulation.

Search Task Objectives and Gameplay

The goal of the search task was to convey to the user that performing simple tasks could be much more difficult with late-stage glaucoma. The potential impact glaucoma has on quality of life can be objectively appreciated. By asking the user to perform the task on a timed basis, it gives the user a sense of urgency, but more importantly provides a measure of how long it would normally take to perform a simple task without impaired vision.

To enhance the experience of the simulator module, ideally an audiovisual clip of TV static would be playing in the TV screen to provide a further incentive for the finding the TV remote. An inability to find the item that can eliminate a source of annoyance can be a frustrating experience and may help users empathize with the difficulties late-stage glaucoma patients suffer from in even trivial situations.

Another impactful feature that would benefit this simulation would be to program the remote to appear in different random, pre-determined places every time the user starts the search task. The remote can be placed in areas with abundant clutter, crevices of couches where there is little color difference, underneath the surface of the coffee table, and nearby objects that may resemble the remote to further illustrate some of the visual difficulties glaucoma patients may face. This introduces an element of variation in the search task that can increase engagement for the users while also reinforcing the task objective.

Limitations & COVID-19

There are several limitations within this study that justify further research and investment. The factors that impacted the overall study will be discussed in the order of (i) unaccounted variables during patient interviews, (ii) development VR mask assets, (iii) limitations with the headset and (iv) importing patient distortion masks into VR space.

Limitations During Patient Interviews

The global pandemic has redefined the boundaries of what is permitted for research. Adjustments had to be made and new considerations taken in light of such events. Due to the high risk of COVID exposure, patient interaction was readjusted to be remote whenever possible. In-person visits were limited to instances in which patient is already at clinic for another appointment. Remaining follow-up interactions were completed remotely.

This introduced variations into ideally standardized variables that simply could not be accounted for. These included light temperature and intensity variation in the assessment environment which can affect sensitivity to light, the distance at which the patient sits away from the screen, the variation of dimensions and quality of monitor devices being used to display the images used for assessment during follow-ups. Further, the differences in displays naturally altered the angle of view and depth of field the patient viewed the assessment images during follow-ups. All of these factors impacted the reliability and validity of patient feedback used to generate the patient specific representations of their glaucoma-induced vision loss.

In addition to the general limitations, there were specific issues that arose within each patient assessment interview. Patient 01 did not experience his visual condition all the time, and did not at the time of the assessment. All of his reports were based on memory or previous anecdotal experience, which may alter the accuracy of the visualization of their experience. Patient 02 explained that the tone of darkness where her vision is compromised depends on the brightness of the environment (I.e. the shade darkens when the environment is darker). This variation may lead to an error in the accuracy of the value represented in that patient's image mask. Patient 03 described experiencing fluctuating distortions in which the missing patches of her vision disappeared and reappeared during certain periods of time. This study did not conceive of developing a standardized method to evaluate temporal fluctuations of vision loss. Temporal variation remains to be a topic worth pursuing in greater depth in the future. Therefore, some level of informed interpretation had to be made when depicting each patient's condition. The fact that the visual assessment itself was conducted using a 2D image also introduced additional limitations. Such a strategy failed to assess vision at the visual periphery and address depth of field. Ideally, the patient would be conducting the exam in a globe or bowl-like space in order to capture depth-of-field information. However, such resources were not implemented when performing the exam in this study.

COVID-19 has also impacted the efficacy of the assessment process in additional ways. Because interviews were conducted remotely, there was a fair amount of trial and error deducing the precise regional boundaries for some of the visual distortions patients were seeing and expressing. We theorize this type of guesswork would be resolved if it were in person and patients could directly point out the limitations of their vision on a screen. Additionally, an extra patient interview in which they are invited to experience the distortion in VR and verify the custom visualizations in the virtual environment would have been a valuable verification step in achieving the overall results and objectives of this study.

Limitations of Importing Patient Distortion Masks into VR Space

Photoshop currently does not contain a mode for producing a transparent blur filter, and thus requires an image to be manipulated in order to produce any blur effect. This means that when importing the resulting distortion mask, the blur information either must be removed, or imported as a filter that contains blur from the assessment scene rather than the actual virtual reality scene. Because blur information significantly contributes to the user's perception of the patient's visual distortion, we opted to import the blur information, even if it contains patches of a different image, as it still provides elucidating information on the limitations of vision patients must learn to manage in their daily lives.

The possibility of resolving the issue with incorporating the blur effect may lie within possible use of C# coding. However, the scope of the current research and knowledge of how to fully implement this strategy prevented full exploration of this option. Nevertheless, this is an option worth examining in future research.

Additionally, there was no COVID-19 safe way to verify whether or not the projected distortion is accurate within the VR space. Ideally, patients would have access to these distortions and be able to address any inaccuracies. The imported masks may also strike the user to be noticeably planar. Whether or not this is accurate to the patient experience remains a question that would need addressing through patient verification from evaluating the distortion within VR space.

Limitations with the Headset

The HTC VIVE currently has two apparent drawbacks – limited peripheral vision and a low-quality front-facing camera. The headset itself limits direct peripheral vision to 110 degrees, which essentially presents the simulated view as if the user was wearing goggles. A wider range of vision can be provided depending on the orientation of the eyes, but it still does not account for full 180-degree field of vision possible with both eyes. A wider range would be ideal for providing a realistic and comprehensive depiction of glaucoma. While this study did not comprehensively assess full peripheral vision for each patient, it would still be ideal to depict it. Future research should seek to broaden the scope of the assessment protocol to check for visual distortion at the wider periphery.

Because the headset is fairly new to market and currently available devices are still novel, the live camera on the HTC VIVE is of low quality. It consists of a fisheye camera capturing at 640x480, containing much low-resolution noise and particle artifacts that may be misconstrued as a visual defect (Figure 121). This is a technological limitation that hopefully can be resolved as better VR headsets are released and higher quality front-facing cameras are utilized. A possible workaround solution could be to take a 360 High-dynamic-range-image (HDRI) photo of the clinic where the device will be used that is then imported into a separate scene. This strategy would provide a higher quality representation of the environment without artifacts that could be confused as a visual defect itself. This would completely eliminate use of the front-facing camera, although possible drawbacks would include possible image distortion and less ability for the user to interact with their surroundings.

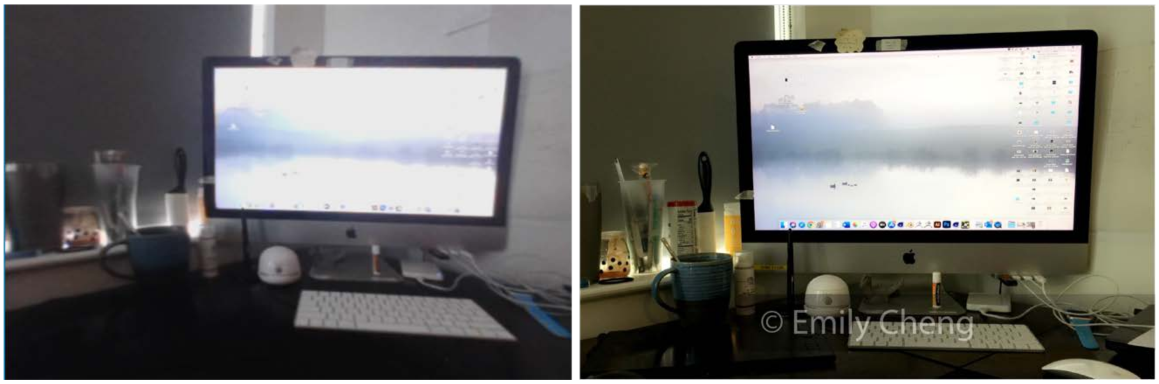


Figure 121. *Comparison of Resolution Between the Fish Eye HTC Front-Facing Camera (Left) and an iPhone 6 (Right).*

Limitations with the Game Engine

Importing multiple external plug-ins and using the SDKs in combination allows for many phenomenal possibilities. However, the complexities found in applying these tools in combination was not found to be completely stable at this point in time. One issue that arose is that the SR Works SDK camera tracking becomes disabled under the Unity URP. Additionally, importing all of the SDKs within one project is sometimes inconsistent and requires occasional reinstallation. The likelihood is that this kind of technology will continue to mature, expand and stabilize—all of which will improve the outlook of implementing VR as an educational tool in ocular healthcare.

Innovations

While some limitations were encountered during certain aspects of this study, there are still notable innovations to this research. To begin, this is one of the first studies using a standardized methodology to create a visualization of patient-specific ocular disease by directly implementing patient feedback through real-time alterations of the image to generate a truly customized image. The amount of published literature showing visualizations of the actual patient experience of glaucoma also has been limited. This is the first study where each patient's specific visual distortion was assessed and concurrently rendered. This study provided for follow up interview sessions with each patient that allowed for direct, precise feedback and verification as to whether or not their visual experience was being depicted accurately.

In addition, this research incorporated a series of patient-specific visualizations in a VR space utilizing recently developed eye-tracking technology. Novel use of GazeVisualizer and TobiiXR SDKs facilitate portraying glaucoma in a novel and more realistic way while also offering users a more dynamic way to visually and spatially interact with the disease. With the distortions tethered to the viewer's focal point, users without glaucoma disease perceive the resulting distortions directly. This is superior to simply presenting a 2D representative image, since viewers do not have the freedom to adjust their focal point to view the obstruction applied to a new point of focus. Experiencing the visual distortion as a 2D image could cause viewers to misinterpret the visual distortion as a shape the patient can divert their attention from, rather than an obstruction that tracks wherever the patient looks because it is bound to a specific distance from their visual focal point.

Finally, there is still a need for material that explains in a concise and engaging way the different types of eye exams used for glaucoma, what those exams test for, and how those tests are indicative of the level of severity they have with their ocular vision. Development of such educational materials may improve patient engagement with preventative treatments by explaining concepts they may otherwise find abstract, allowing them to make more informed decisions surrounding their diagnosis of early onset glaucoma.

Future Implications for Education

This study serves as a prototype and a proof-of-concept that various visual conditions can be simulated in the VR space and augmented upon in an educationally impactful way. This application should act as a starting point to be further developed as an accurate simulation tool that can be expanded include content of other vision impairments such that physicians and healthcare providers can utilize VR technology as a tool for promoting compliance with treatment protocols and increased empathy in patient care.

A useful future direction worth investigating would be exploring the benefits and possibilities of simulating glaucoma disease progression. This would involve identifying a group of eligible early onset patients whose visual impairment can then be documented over time. The visual data and test results could provide illuminating information on patient specific long-term experience of the disease, which could be educationally powerful.

Currently, there are companies in the process of developing VR based applications for administering visual field testing. While the functions of these developing applications are different, the research conducted within this study could be potentially incorporated into those newly conceived platforms as a supplementary element to already existing content.

Conclusion

Glaucoma is a widespread disease that can have severe late-stage impacts on patient quality of life. Yet, due to its sometimes slow-progressing nature, inflicted patients often may not have the sense of urgency needed to combat the disease early on. There is a body of existing visual material that aims to explain this disease to early-onset patients, their families, and healthcare providers. However, while this has the potential to possibly encourage better adherence to early treatment, such visualizations fail to provide a coherent narrative of how ongoing disease progression will impede and affect activities of daily living because of the limitations of a 2D image. Furthermore, they fail to provide a coherent picture of the first-person patient experience, partly because of the nature of how they were developed without a clear methodology, including patient assessments of visual loss.

This research addresses the lack of existing visual resources by developing a standardized visual assessment protocol that documents glaucoma-induced visual distortions through the methods of interview-based feedback, producing patient-specific images of visual distortions, and implementing those distortions within a VR environment tailored as an educational platform. This study can contribute to a greater understanding of various patient experiences of glaucoma by using a methodological approach that better captures some of their reported visual experiences. It also can benefit patients and secondary audience members by encouraging learning through an engaging and innovative use of technology.

The developed application serves as an initial building block for some of the applicable uses of novel VR technology in depicting glaucoma. It has the potential to be referenced and enhanced for improved simulation, expanded to be applied into other ocular diseases, or incorporated into other existing or developing VR applications of ocular diseases. As the use of virtual reality in healthcare continues to grow, this research can contribute to the future development of tools for augmenting the potential of biomedical communication.

Appendices

Appendix A: Final Patient Visual Assessment Script

Introduction:

Hi, my name is Emily! I am a graduate student at the Johns Hopkins Department of Art as Applied to Medicine and I am working with Dr. Ramulu to create a tool that can better depict the condition of glaucoma in a virtual reality setting. I would like to thank you very much for participating in this study. Your contribution will make a big difference to fellow patients and healthcare practitioners. Today, I will present to you a series of photos in which we can collectively identify where you think you experience visual deficits and what they look like. This session should take about 1 - 1.5 hours. We will have you sitting 2 feet away from the monitor, and you will be provided a single-use patch to help you achieve better focus on the eye you are using (you will be switching eyes for comparison).

During this session, I will be spending most of my time marking areas and noting descriptions while blocking out the deficits. Everything will look pretty rough. After this session, I will use today's notes to refine the image. We would like to reach out to you after to ensure the refinements are an accurate portrayal of your condition. Is this something you are okay with?

Do you have any questions before we begin?

Explanation

Once you are ready, I will pull up the first image on the screen.

This is a focal point (the dot in the center). You will be asked to focus on this point when trying to identify the surrounding visual patterns.

This is a labelled grid, where you can help us locate your impairment. The labels here indicate LEFT for L, and RIGHT for R. 1, 2, 3, 4 are consecutive labels for the quadrant space.

Once you identify the quadrants where you see impairment, we will isolate out those areas (using this cursor) and begin breaking down the content of that impairment.

Any questions?

First Task: Shimmer

I will now present to you a default shimmering background. Please place the patch on your impaired eye, focus on the focal point, and view with the normal eye.

Once you are ready, switch the patch to be placed on the normal eye.

1) With your eye focused on the middle focal point, <u>can you identify using the quadrant labels where you see impairment?</u>
    a. No shimmer, reduced shimmering, missing shimmer
    b. Objective is to identify the locations – **all in green**

[Patient identifies location]

2) <u>Please keep focused on the middle focal point. Can you now try and best describe what you are experiencing in that deficit area?</u>
    a. You may switch the patch between your normal and impaired eye to compare and contrast the differences in that area.

Second Task: Scene 1 grocery aisle normal

For the second task, we will be taking a look at some items in the grocery aisle. If you may please place your patch on your impaired eye and look at the image with the normal eye.

3) Can you list the names of these products and they types of products they are? (e.g Skippy – peanut bar jar)

Second Task: Scene 1 grocery aisle impaired

Now, please switch your eye patch and view the scene with your impaired eye. Please remain focused on the focal point.

4) Can you identify using the quadrant labels where you see impairment?
    a. **Use WHITE to fill in mask (mask is inverted**)
5) Can you provide a brief description of what you are experiencing in that area?
    a. You may switch the patch between your normal and impaired eye to compare and contrast the differences in that area.

I will now pull up a series of distortions based on your description. Can we go over these and have you confirm whether or not is reflects your impairment accurately?

6) <u>Questions: (is it more like A or B)</u>
    a. Is it more or less intense?
    b. What is the <u>full area</u> in which you see the impairment? (including the smallest distortions) – **draw with green line**
    c. How about the area in which you see <u>moderate</u> distortion? **Yellow line**
    d. Areas with <u>extreme</u> distortion? **Red line**

e. Where in this quadrant do you NOT see this distortion

    i. What do you see instead?

Post-questions:

1. Is there anything related to the anatomy of the eye that you would like to understand about glaucoma?
2. Are there images that you think might help you better understand the condition?

End:

Thank you for taking the time to answer all these questions. As we have stated in the beginning, we would like to take these notes and develop a more refined image to then confirm with you later. Would you be okay if we stayed in touch and to have us reach out to you in a couple weeks?

Thank you again for your time and attention!

Appendix B: Patient Visual Assessment Notes

Patient 01

Patient 01 reports seeing occasional 3-4 lines that look like waves in his left superior temporal quadrant. He describes the lines as lightning, translucent, and slightly lighter than everything he looks at. He also experiences this visual distortion in the temporal region, they don't appear every day and only last a few minutes when they do. The lines also sometimes glide towards the inferior right nasal quadrant in R3 and then disappear. These descriptions eventually were deciphered to be floaters and were ultimately left out of the final mask. The Patient also described experiencing a cloudiness in the left eye, in which he attempts to blink out whenever it occurs. This cloudiness also does not happen every day and only persists for a few minutes when it does. The patient describes it taking on a cameo shape, and is a fixed, static image when it appears. Verified through a second session, this patient described the image rendition of the cloudiness to look very accurate to what he remembers.

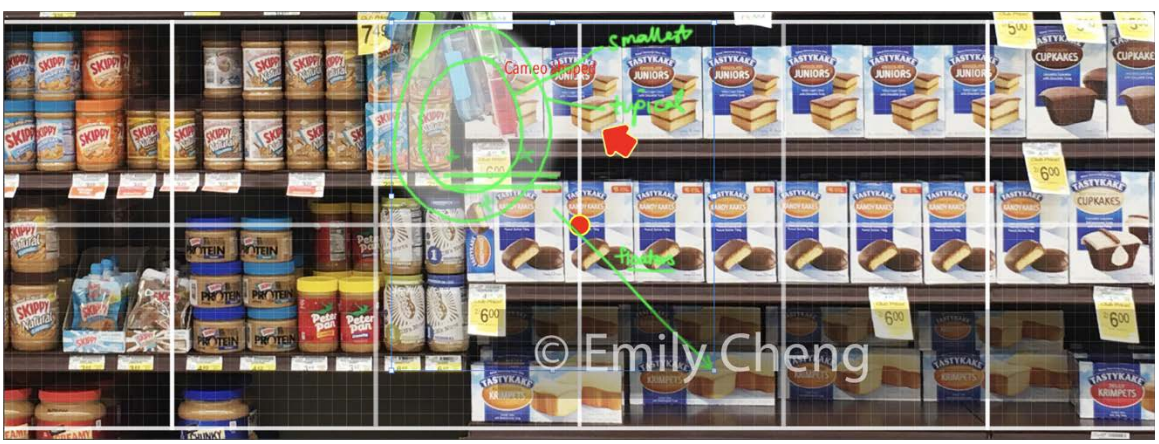


Figure 122. *Patient 01 Session 1 Notes. Text not intended to be read.*

Patient 02

Patient 02 experiences obstruction that is reported to look grey and foggy. There are darker and lighter spots that look marbled and take on swirl shapes. Regionally, the patient describes seeing this greyness take on the form of a slant that goes from the superior nasal portion of R2 that tends to the upper 3/4ths of L3.

In the second session, the patient described her visual obstruction to be more cloudy, thinner than what I had presented to her. The tone of grey is slightly darker. The obstruction has slower blurs that fade off gradually. Her upper periphery shows lighter and foggy tone, where she describes that can tell there is something there but cannot identify what it is. Her far left periphery is not completely black, but very foggy and is described to be something that looks smudged. She verified the darkness of the tone in the image for what she feels to be accurate to her left periphery. In her right periphery, she can notice movement (moving cursor), but cannot distinguish color. She describes the vision to be a light gray fog that’s very blurry. The patient also described seeing the tone of darkness change depending on the brightness of her environment. The greyness seems darker in darker environments, and lighter in brighter ones.

Figure 123. *Patient 02 Session 1 Notes. Text not intended to be read.*

Patient 03

Patient 03 describes a sheer black cover on R1 and a grey screen like substance for R1 and L2. She reports L2 looking like a tinted window or the sunset. Her left side is reported to be normal. In R2, she described a cloudiness or a thick fog, similar to being in an airplane. There is an inverted J-shade that obstructs her vision, comprised of a lighter grey tone. The regionality of this shape was confirmed by the patient in the first session. Everything above the strip took on a hammock shape that she describes feels as if she is underwater. Patient also reports a lower level of contrast in her impaired eye. During the second session, she corrected the tone to be darker, and discussed adding in a blur around the edges.

Figure 124. *Patient 03 Session 1 Notes. Text not intended to be read.*

Patient 04

Patient 4 marked L2 and R1 as locations containing distortions and his obstructions to seem void-like, as if it were dusk and have a charcoal color. He describes things blurring out or being out of focus, as if he had a bad prescription on glasses. He reports feeling like he's seeing through tunnel vision with colors being bright in areas where he feels his vision is normal, but become more muted as they creep towards areas where he experiences vision loss. Patient was able to confirm the locations of the defect well. On the second session, patient reported the obstruction was comprised of a lighter grey and that instead of seeing that obstruction actively, it rather just feels like the vision there is absent.

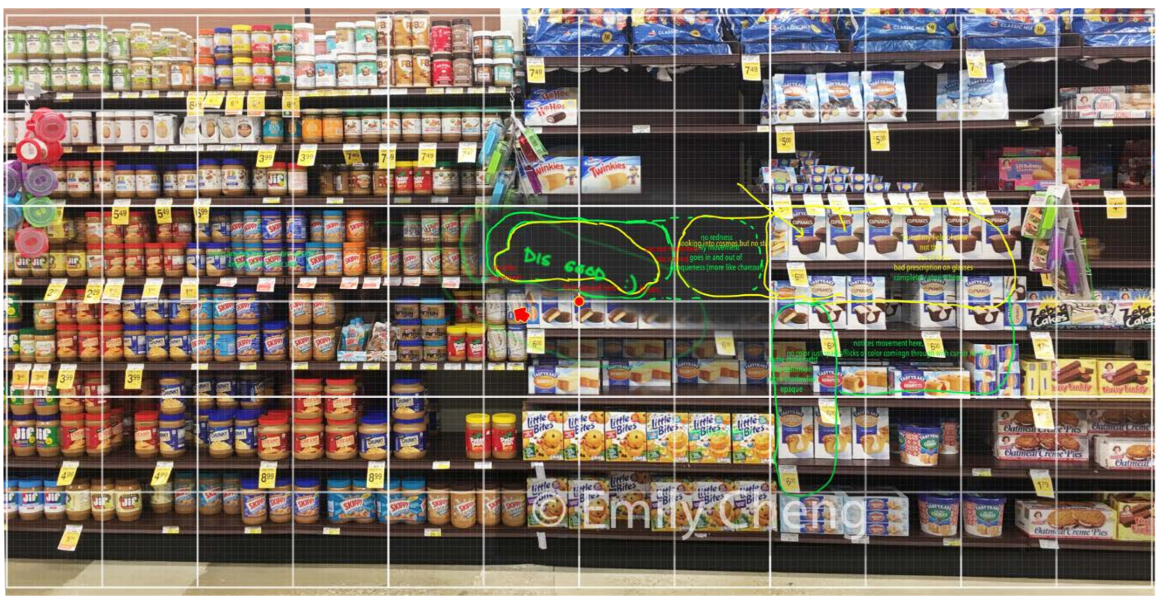


Figure 125. *Patient 04 Session 1 Notes. Text not intended to be read.*

Appendix C: Virtual Reality Application Rough Concepts

Sketch Renditions of User Interface Design

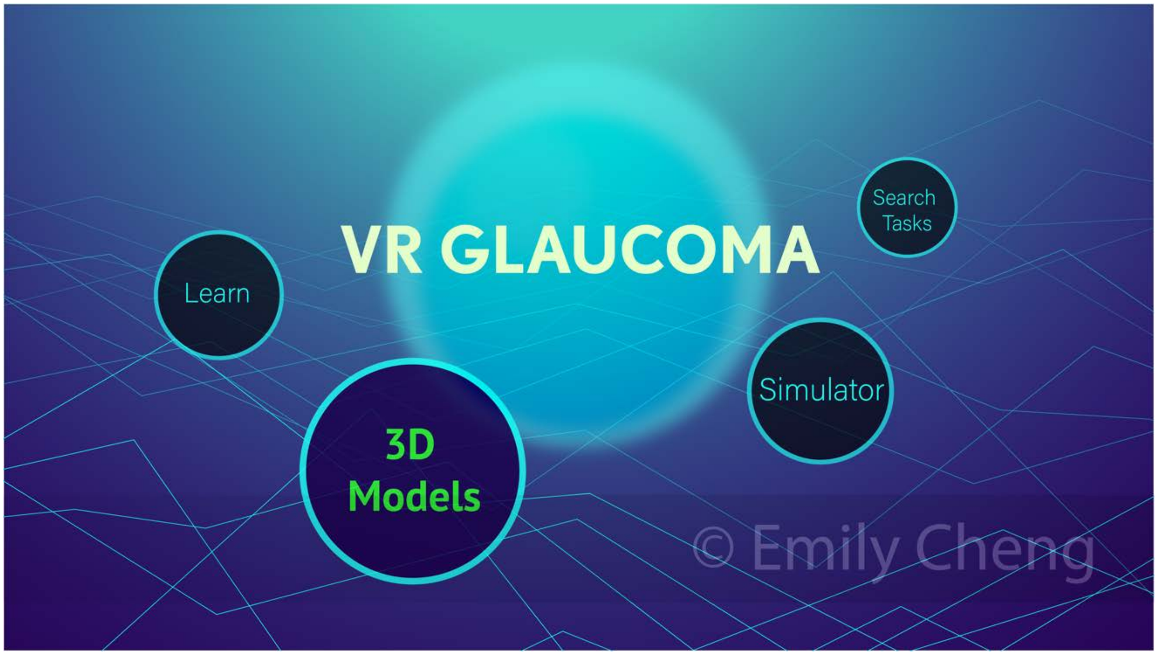


Figure 126. *Original Rough Concept of Main Scene.*

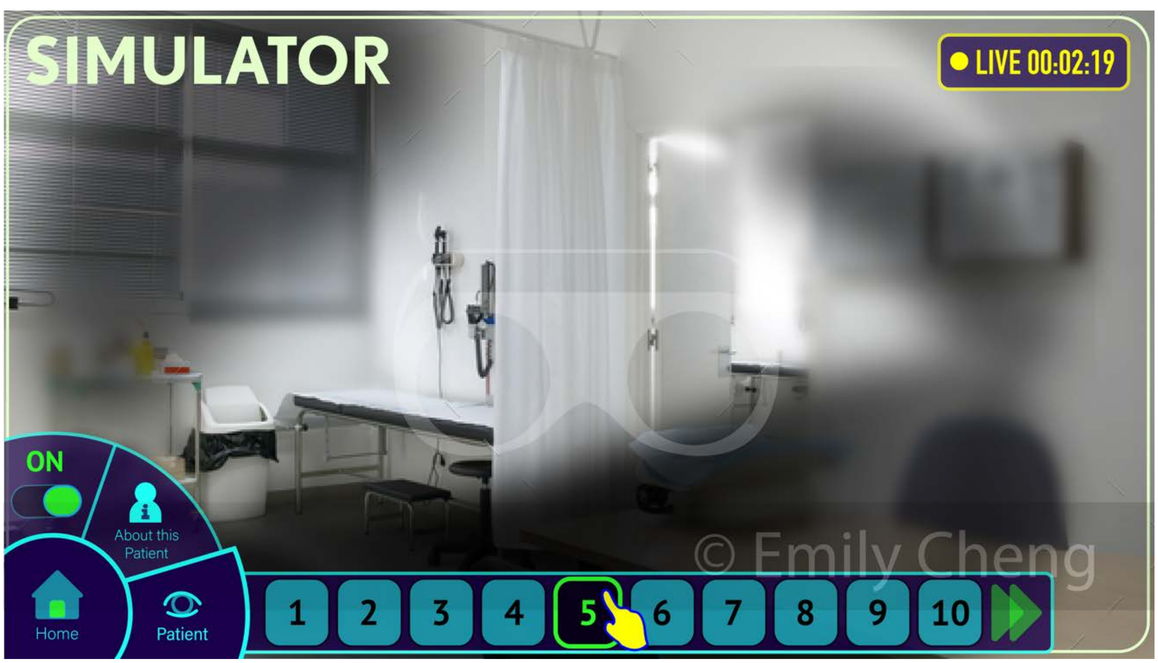


Figure 127. *Original Rough Concept of Live-Camera Module.*
Text not intended to be read.

Figure 128. Original Rough Concept of Search Task Simulator Module. Text not intended to be read.

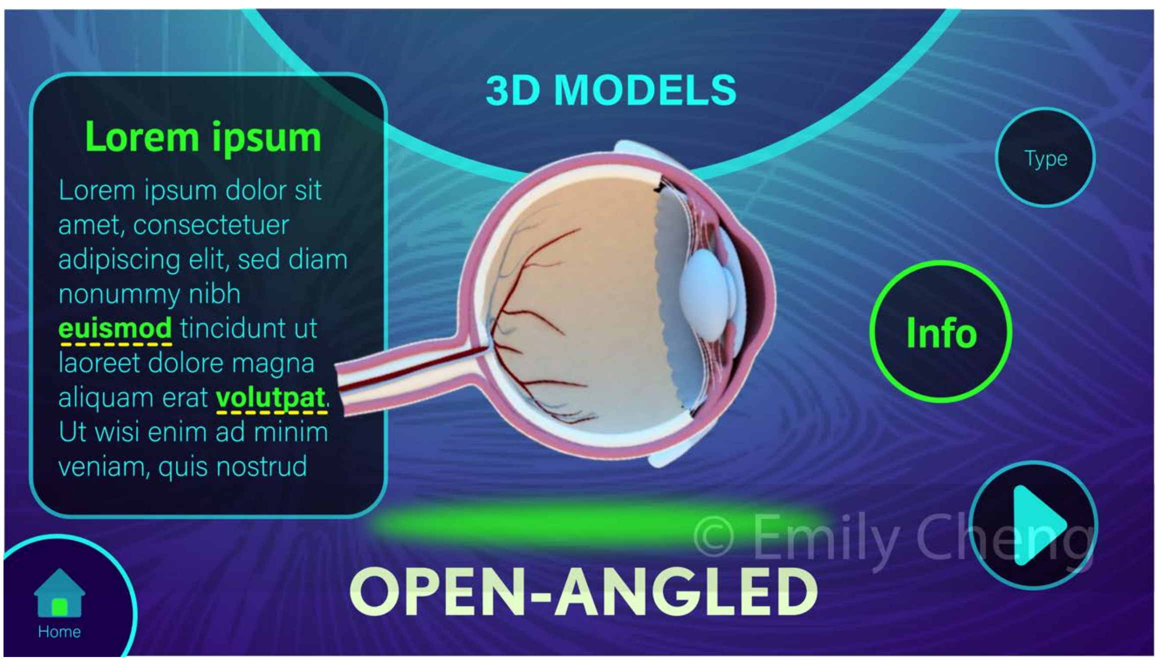


Figure 129. Original Rough Concept of Patient Education Module. Text not intended to be read.

Appendix D: "Timer" Grabbable Remote Script

```
using System.Collections;
using System.Collections.Generic;
using UnityEngine;
using UnityEngine.UI;
using Valve.VR;

public class Timer : MonoBehaviour
{

   float currentTime = 0f;
   public float startingTime = 30f;

   public Text countdownText;

   public bool canGrab = false; //so that you cannot grab to begin with
   public bool grabbed = false; //if grabbed is true then the timer is stopped

   public bool canFlash = true; ///  to make sure flashing doensn't conflict with
green
   /// </summary>
   public int flashingNumbers = 0;
   public float FNTimer = 30f; //f stands for float

   public Color invisible = Color.red;



   void Start()
   {
      currentTime = startingTime; //allows us to make starting time whenever
we want. current time is the one that changes and updates text object
      invisible.a = 10f;
   }


   void Update()
   {
      if
(SteamVR_Actions._default.GrabPinch.GetStateDown(SteamVR_Input_Sources.
Any))
      {
         if (canGrab == true && currentTime >=0)/// if you can grab it and time is
above 0, text becomes GREEN
         {
            grabbed = true;
            canFlash = false;
```

```
            countdownText.color = Color.green;

         }

         if (canGrab == true && currentTime <0) ///if you grab it and time is
negative, run yellow text
         {
            grabbed = true;
            canFlash = false; //since we don't want the color to flash during this
time, technically don't need it but it's
            countdownText.color = Color.yellow;

         }

      }

      if(currentTime < 0)
      {
         canFlash = false;
         countdownText.color = Color.yellow;

      }

      if (grabbed == false)
      {
         currentTime -= 1 * Time.deltaTime; //current time minus the "amount of
time that has passed" to account for fps
         countdownText.text = currentTime.ToString("0.0");
      }// if you can't grab  it the timer just stops counting and will show how
much time is left before 0

   }

   void FixedUpdate()
   {

      if(currentTime <= 10 && flashingNumbers < FNTimer/2 && canFlash ==
true)
      {
         countdownText.color = Color.red;
         flashingNumbers += 1;
      }

      if(currentTime <= 10 && flashingNumbers >= FNTimer/2 && canFlash ==
true)
      {
         countdownText.color = Color.yellow;
         flashingNumbers += 1;
```

```
      if (flashingNumbers >= FNTimer)
      {
        flashingNumbers = 0;
      }
    }
  }

  void OnTriggerEnter(Collider other)
  {
    if(other.gameObject.CompareTag("Hand"))
    {
      canGrab = true;
    }
  }//when hand on object - grabbable

  void OnTriggerExit(Collider other)
  {
    if (other.gameObject.CompareTag("Hand"))

      canGrab = false;
    }
  }//when hand not on object - no longer grabbable
```

Appendix E: “Gaze Visualizer” Distance Modifications Script

```
// Copyright © 2018 – Property of Tobii AB (publ) - All Rights Reserved

using Tobii.XR.GazeModifier;
using UnityEngine;

namespace Tobii.XR
{
   [RequireComponent(typeof(SpriteRenderer))]
   public class GazeVisualizer : MonoBehaviour
   {
      private enum GazeVisualizerType
      {
         Default,
         Bubble,
      }

      public bool ScaleAffectedByPrecision;

#pragma warning disable 649
      [SerializeField] private GazeVisualizerType _visualizerType;

      [SerializeField] private bool _smoothMove = true;

      [SerializeField] [Range(1, 30)] private int _smoothMoveSpeed = 7;
#pragma warning restore 649

      private float ScaleFactor
      {
         get { return _visualizerType == GazeVisualizerType.Bubble ? 0.03f : 0.003f;
}
      }

      private float _defaultDistance;

      private Camera _mainCamera;

      private SpriteRenderer _spriteRenderer;
      private Vector3 _lastGazeDirection;


      public float OffsetFromFarClipPlane = 10f;
      private const float PrecisionAngleScaleFactor = 5f;

      private void Start()
      {
         _mainCamera = CameraHelper.GetMainCamera();
```

```
            _spriteRenderer = GetComponent<SpriteRenderer>();

            _defaultDistance = _mainCamera.farClipPlane - OffsetFromFarClipPlane;
        }

        private void Update()
        {
            var provider = TobiiXR.Internal.Provider;
            var eyeTrackingData =
EyeTrackingDataHelper.Clone(provider.EyeTrackingDataLocal);
            var localToWorldMatrix = provider.LocalToWorldMatrix;
            var worldForward =
localToWorldMatrix.MultiplyVector(Vector3.forward);
            EyeTrackingDataHelper.TransformGazeData(eyeTrackingData,
localToWorldMatrix);
            var gazeModifierFilter = TobiiXR.Internal.Filter as GazeModifierFilter;

            if (gazeModifierFilter != null)
gazeModifierFilter.FilterAccuracyOnly(eyeTrackingData, worldForward);

            var gazeRay = eyeTrackingData.GazeRay;
            _spriteRenderer.enabled = gazeRay.IsValid;
            if (_spriteRenderer.enabled == false) return;

            SetPositionAndScale(gazeRay);

            if (ScaleAffectedByPrecision && gazeModifierFilter != null)
            {

UpdatePrecisionScale(gazeModifierFilter.GetMaxPrecisionAngleDegrees(eyeTra
ckingData.GazeRay.Direction, worldForward));
            }
        }

        private void SetPositionAndScale(TobiiXR_GazeRay gazeRay)
        {
            RaycastHit hit;
            var distance = _defaultDistance;
            if (Physics.Raycast(gazeRay.Origin, gazeRay.Direction, out hit))
            {
                distance = hit.distance;
            }

            var interpolatedGazeDirection = Vector3.Lerp(_lastGazeDirection,
gazeRay.Direction,
                _smoothMoveSpeed * Time.unscaledDeltaTime);

            var usedDirection = _smoothMove ?
interpolatedGazeDirection.normalized : gazeRay.Direction.normalized;
```

```
            transform.position = gazeRay.Origin + usedDirection * distance;

            transform.localScale = Vector3.one;
               //* distance * ScaleFactor;

            transform.forward = usedDirection.normalized;

            _lastGazeDirection = usedDirection;
        }

        private void UpdatePrecisionScale(float maxPrecisionAngleDegrees)
        {
            transform.localScale *= (1f +
GetScaleAffectedByPrecisionAngle(maxPrecisionAngleDegrees));
        }

        private static float GetScaleAffectedByPrecisionAngle(float
maxPrecisionAngleDegrees)
        {
            return maxPrecisionAngleDegrees *
Mathf.Sin(maxPrecisionAngleDegrees * Mathf.Deg2Rad) *
PrecisionAngleScaleFactor;
        }
    }
}
```

Appendix F: "Change Image" Sprite Renderer Script

```
using System.Collections;
using System.Collections.Generic;
using UnityEngine;
using UnityEngine.UI;


public class ChangeImage : MonoBehaviour
{

    public Sprite Patient1;
    public Sprite Patient2;
    public Sprite Patient3;
    public Sprite Patient4;
    public Sprite Patient5;
    public GameObject Patient1image;
    public GameObject Patient2image;
    public GameObject Patient3image;
    public GameObject Patient4image;
    public GameObject Patient5image;
    public Text Generalreport;

    public SpriteRenderer AssignGaze; //names here "Image" don't need to be
    //consistent with what's named on hierarchy; capital doesn't matter but
consistency important

    public void MakePatient1()
    {
        AssignGaze.sprite = Patient1;
        Generalreport.text = "PATIENT 1 TEXT";
        Patient1image.gameObject.SetActive(true);
        Patient2image.gameObject.SetActive(false);
        Patient3image.gameObject.SetActive(false);
        Patient4image.gameObject.SetActive(false);
        Patient5image.gameObject.SetActive(false);

    }

    public void MakePatient2()
    {
        AssignGaze.sprite = Patient2;
        Generalreport.text = "PATIENT 2 TEXT";
        Patient2image.gameObject.SetActive(true);
        Patient1image.gameObject.SetActive(false);
        Patient3image.gameObject.SetActive(false);
        Patient4image.gameObject.SetActive(false);
        Patient5image.gameObject.SetActive(false);
```

```
    }

    public void MakePatient3()
    {
        AssignGaze.sprite = Patient3;
        Generalreport.text = "PATIENT 3 TEXT";
        Patient3image.gameObject.SetActive(true);
        Patient2image.gameObject.SetActive(false);
        Patient1image.gameObject.SetActive(false);
        Patient4image.gameObject.SetActive(false);
        Patient5image.gameObject.SetActive(false);

    }

    public void MakePatient4()
    {
        AssignGaze.sprite = Patient4;
        Generalreport.text = "PATIENT 4 TEXT";
        Patient4image.gameObject.SetActive(true);
        Patient3image.gameObject.SetActive(false);
        Patient2image.gameObject.SetActive(false);
        Patient1image.gameObject.SetActive(false);
        Patient5image.gameObject.SetActive(false);

    }

    public void MakePatient5()
    {
        AssignGaze.sprite = Patient5;
        Generalreport.text = "PATIENT 5 TEXT";
        Patient5image.gameObject.SetActive(true);
        Patient4image.gameObject.SetActive(false);
        Patient3image.gameObject.SetActive(false);
        Patient2image.gameObject.SetActive(false);
        Patient1image.gameObject.SetActive(false);

    }
}
```

Appendix G: 3D Model Asset References

Search Task Simulator

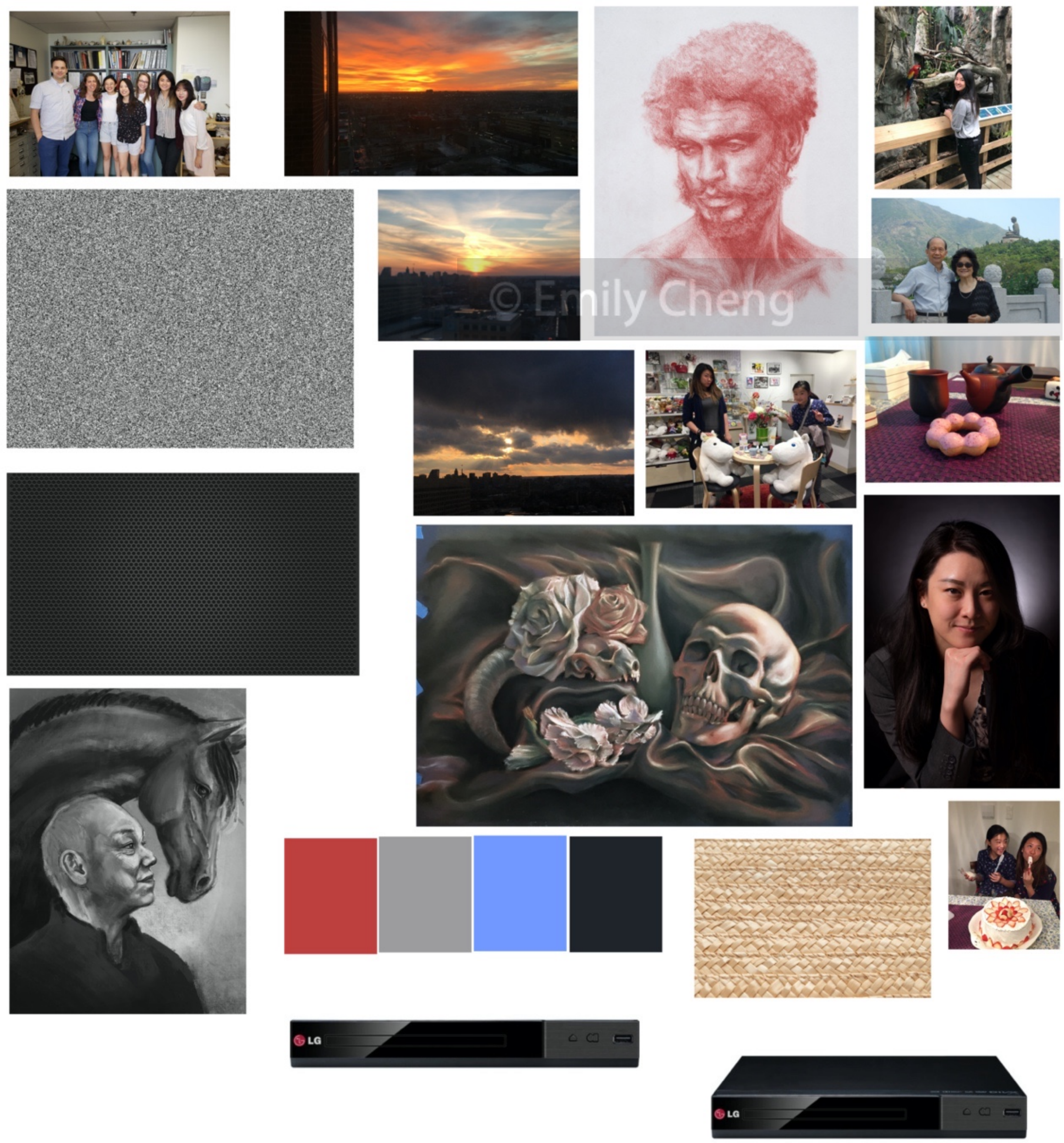


Figure 130. *Compiled Images Used for UV Wrapping in Blender – Spread 1.*

Figure 131. *Compiled Images Used for UV Wrapping in Blender – Spread 2.*

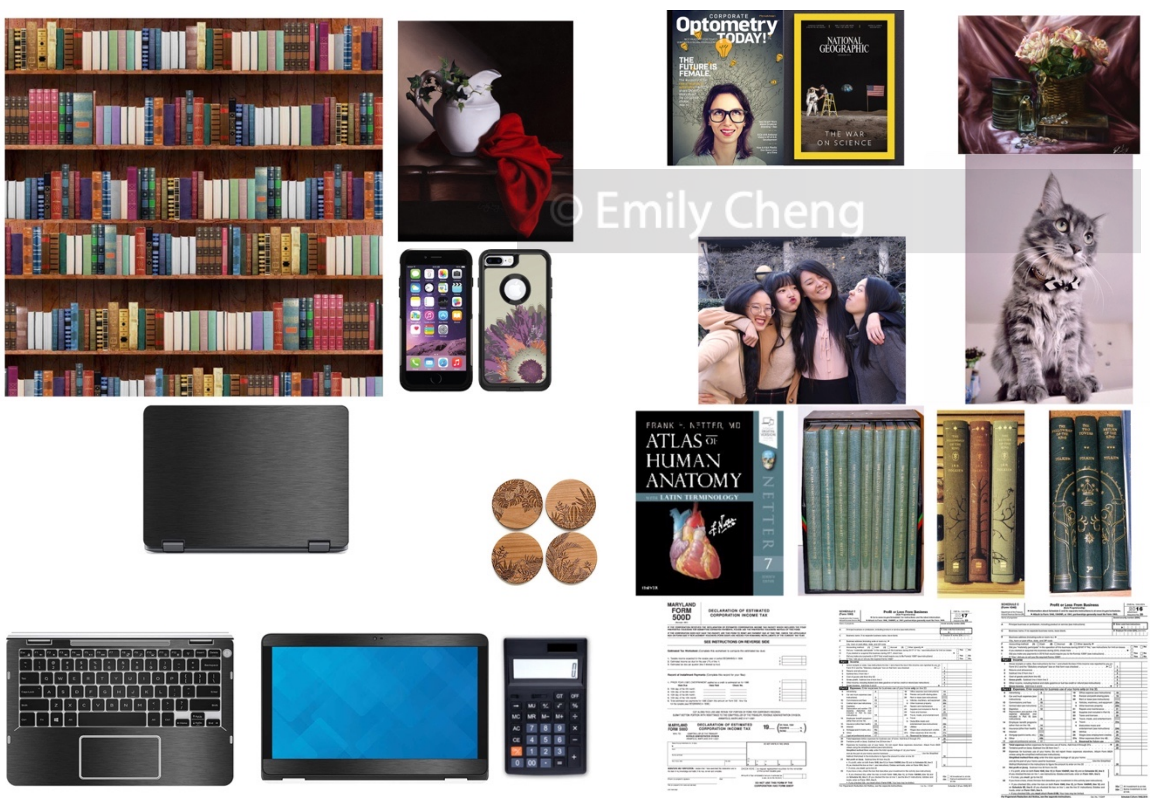


Figure 132. *Compiled Images Used for UV Wrapping in Blender – Spread 3.*

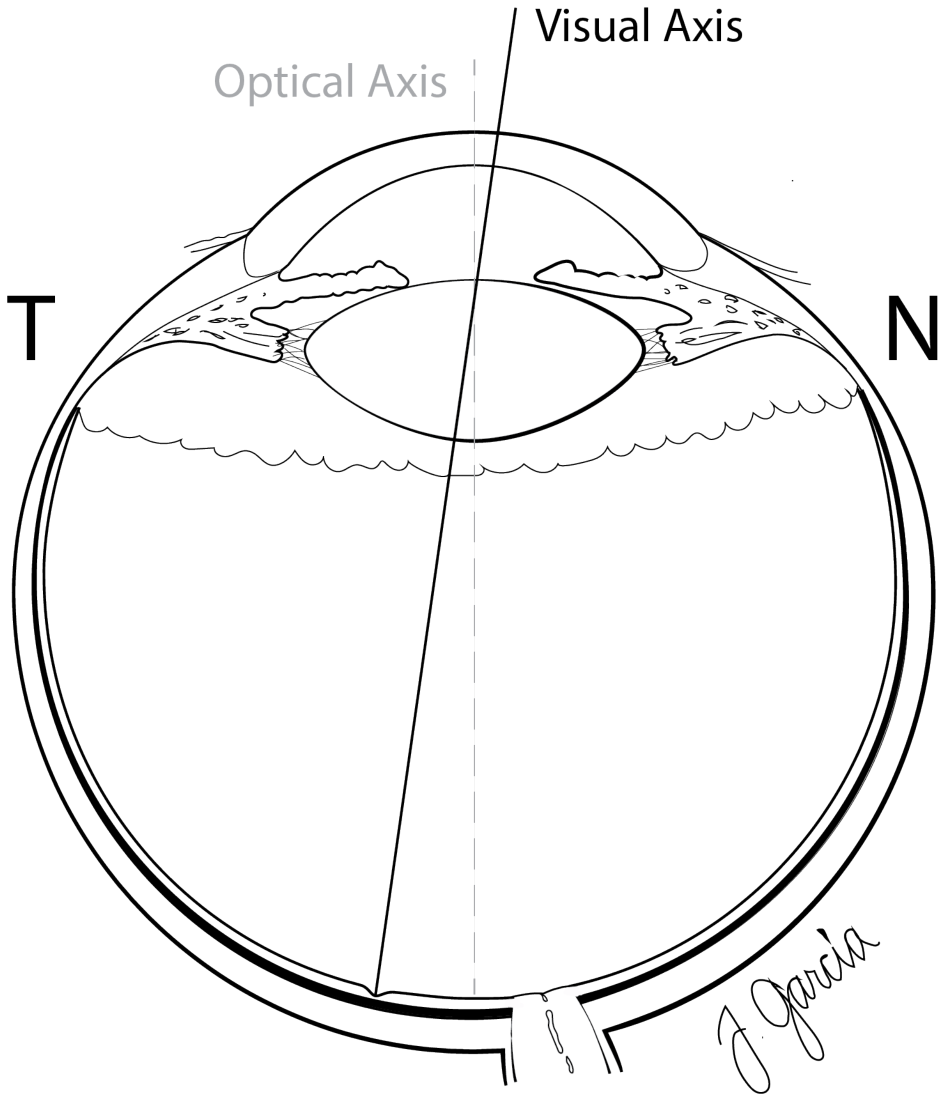


Figure 133. *Reference Image for Initial 3D Modeling by Juan Garcia*

Appendix H: Animation

Written Scripts

Introductory Narrative – Physiologically Healthy Vision

(VISUAL: ¾ view of whole eye with light entering through front)

Glaucoma affects normal vision, and if left untreated, is the leading cause of irreversible blindness.

(VISUAL: rotate and reveal 3D cross section of eye—with light entering and hitting macula. Then zoom in to show signal transmitted through optic nerve as a glow)

In **Normal Vision**, **light** enters the eye and is focused on the **retina**. Several nerve cells in the retina, called **retinal ganglion cells,** detect the light and transmit signals through a series of nerve fibers exiting the eye through the **optic nerve.** These signals are sent to the brain to be interpreted as vision.

(VISUAL: inset of normal)

(VISUAL: Rotate eye and zoom in to back of retina--with optic disk, macula, vessels, nerve fiber tracks. Glowing signals from macula to optic disk. Label for Intraocular pressure with an arrow that moves up. Glowing around certain fibers stop as pressure increases)

Glaucoma occurs when the fluid inside the eye, called **intra-ocular pressure,** rises and compresses the **optic nerve head**. The **retinal ganglion cells** become crushed and can no longer transmit signals for vision to occur**.** When the fibers become damaged, areas of vision become affected.

(VISUAL: Inset of damaged visual field)

The front part of the eye is bathed in a fluid called the aqueous humor. This fluid is produced by structures behind the iris called **ciliary bodies.** It flows in front of the iris and is then drained through a sieve-like structure called the **trabecular meshwork.** The build-up of pressure inside the eye is controlled by draining this fluid.

When the drainage of this fluid is disrupted, pressure builds up inside of the eye. This can end up crushing the optic nerve.

Disruption of drainage occurs at the area called the **angle**. Blockage can occur in one of two ways, leading to different types of glaucoma.

Open angled

In open-angled glaucoma, the **trabecular meshwork** becomes partially blocked, while the drainage angle formed by the cornea and iris remains open. The blockage of the trabecular meshwork causes an increase of AH humor buildup within the eye, crushing the **retinal ganglion cells** in the optic nerve, resulting in blindness.

This type of glaucoma is slow-progressing and usually difficult to notice before significant damage has occurred. Disease progression can happen through the course of many years. It is also the most common type of glaucoma.

Close angled

In close-angled glaucoma, the trabecular meshwork remains unaffected, while the **drainage angle** formed by the cornea and iris closes due to the forward bulging of the iris. This results in an **immediate rise of intraocular pressure** and is a medical emergency.

Testing

Two important tests can reveal important information about the severity of glaucoma. The first is **optical coherence tomography (also known as OCT).**

(VISUAL: OCT test)

This test is effective at evaluating critical early stagesof glaucoma. In OCT, your ophthalmologist evaluates two types of images.

(VISUAL: Pan in and place OCT inset next to optic disk)

One represents a **cubic area** around your optic nerve. This image is marked by a range of colors. Normally, there is a greater density of **retinal ganglion cells,** the nerve cells that are responsible for vision, surrounding blood vessels supplying the retina. This is indicated by warmer colors, red, orange and yellow.

When the optic nerve is **cupped due to increased pressure**, retinal ganglion cells (responsible for vision) are affected and possibly reduced. A low density of retinal ganglion cells is indicated by cooler colors: aqua and blue. This is an indicator for glaucoma.

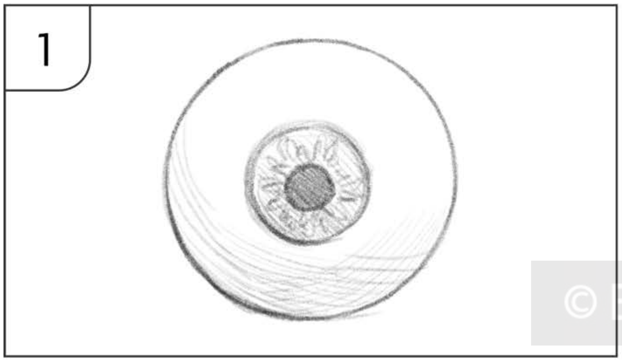
Another part of the OCT test represents a cross-section taken around the optic nerve. When flattened into this image, it is possible to evaluate the relative density of retinal ganglion cells exiting the optic disc. As these cells die off, peaks in the chart are flattened. Usefulness of the OCT test, however, tends to bottom out as glaucoma progresses.

(VISUAL: Pan out to show macular region. Visual field test is shown next to optic disk)

This is when the second test, the **visual field test**, becomes important. For a visual field test, your ophthalmologist compares the 4 quadrants surrounding the critical part of the retina responsible for central vision, known as the **macula lutea**. Nerve fibers conduct signals from different parts of the macula. Different areas of damaged nerve fiber tracts are shown as progressively darker regions in the test. These dark areas correlate with different areas of compromised vision.

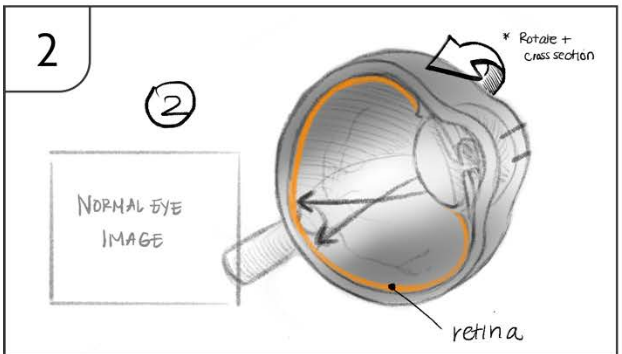
Finally, as the disease inches into late stage, visual field tests provide less useful information, and treating the disease fully relies on verbal descriptors provided by the patient. Testing is therefore important as it allows for early quantification of the disease and facilitates preventative measures to be taken.

Storyboard for Physiologically Healthy Eye "What is Glaucoma?"



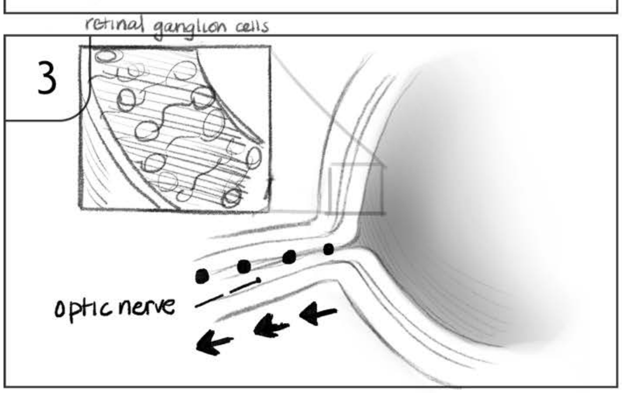
SCRIPT:
Glaucoma affects normal vision, and if left untreated, is the leading cause of irreversible blindness

NOTES:
First scene is just whole eye to ground the viewer



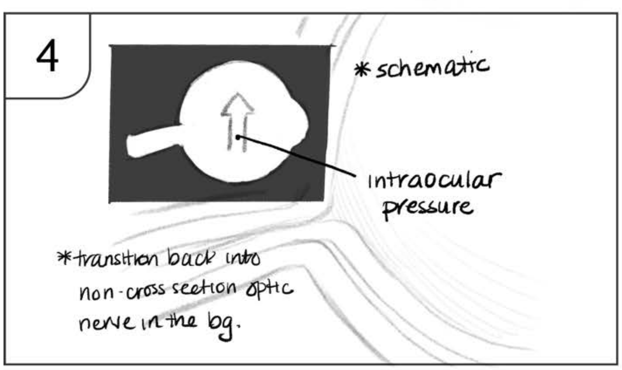
SCRIPT:
In normal vision, light enters the eye and is focused on the **retina.**

NOTES:
Eye rotates and cross section fades in. Retina glows (orange) when mentioned.
Arrow is a 2D animation - placed on a canvas



SCRIPT:
Several nerve cells in the retina, called **retinal ganglion cells**, detect the light and transmit signals through a series of nerve fibers exiting the eye through the **optic nerve**. These signals are sent to the brain to be interpreted as vision.

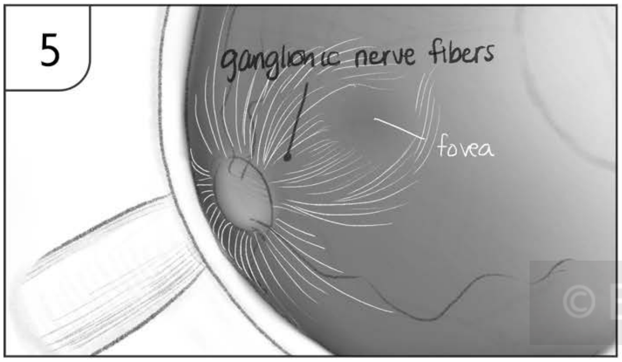
NOTES:
label the rgc in cross section
show rgc having fiber tracts



SCRIPT:
Glaucoma occurs when the rise of **intraocular fluid pressure** compresses the **optic nerve head**.

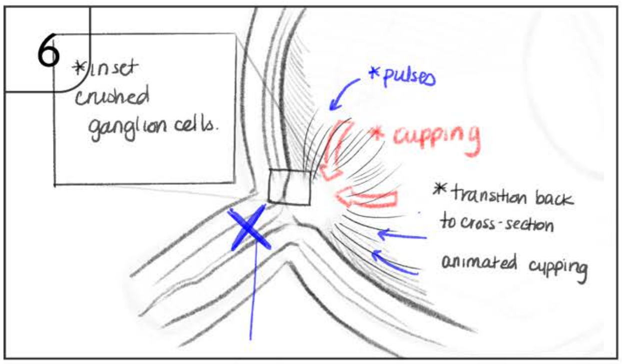
NOTES:
2D animated arrows on a canvas?

Figure 134. *3D Animation "What is Glaucoma?" Storyboard Page 1.*



SCRIPT:
The retinal ganglion cells exiting through the optic nerve...

NOTES:
Rotate the eye to zoom into retinal ganglion cells



SCRIPT:
...become crushed and can no longer transmit signals for vision to occur. When the nerve fibers become damaged, areas of vision become affected.

NOTES:
Glow over the area of retinal ganglion cells. Texture of RGCs appear.
Inset appears in second sentence.

__Figure 135__. 3D Animation "What is Glaucoma?" Storyboard Page 2.

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Vita

Emily Cheng was born in Diamond Bar, California. While she was predisposed to the arts and crafts, she has always had an affinity towards the conceptual complexity of biological mechanisms, along with a curiosity about how the mind worked. This led her down a path of receiving her Bachelor of Science in Neuroscience at University of California, Los Angeles. She spent this time getting involved in the medical community through clinical research, public service, and inevitable design work.

Emily spent many of her extracurricular hours developing informational pieces for her research organizations and community clubs. As the president of Team HBV, a nonprofit that raises awareness of the importance to get vaccinated for hepatitis B, she developed diagrams, brochures and even short comics in an effort to reconfigure complex scientific material into a digestible narrative for patients. The same task carried over into her clinical benchwork at the UCLA department of pediatric neurology, where, aside from conducting statistical analyses and publishing papers, she designed banners, posters, and patient education material for the department clinic and pediatric neurology charity events. It was in this time she learned of the field of medical illustration, and felt that it was a calling for her.

To develop a competitive portfolio and prepare herself for the pursuit of this career, Emily enrolled in Santa Monica College and Los Angeles Academy of Figurative Art to obtain the necessary scientific background and atelier experience.

Soon after, she matriculated into Johns Hopkins University for the Medical and Biological Illustration graduate program in the Department of Art as Applied to Medicine. In her first year, Emily earned the Frank Netter Scholarship award for her exemplary performance in Human Anatomy. She also obtained an Award of Excellence for her biological piece "Life Cycle of the Flower Hat Jelly" and an Award of Merit for her anatomical plate "Pathway of the Accessory Nerve CNXI" in the student categories at the 2020 Annual Association of Medical Illustrators Conference. She is also honored to be named a 2021 Vesalian Scholar granted by The Vesalius Trust for Visual Communication in the Health Science from this thesis proposal. Emily is a candidate to receive her Master of Arts in Medical and Biological Illustration in May of 2021.

After graduation, Emily hopes to take her skills and experience to contribute to the VR and 3D industry and bolster the potential it has in fostering patient education and garnering public interest.